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The effect of prototype fidelity on usability evaluation in product development

Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Technology.

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Abstract of master's thesis

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Building prototypes is an important part of any product development process and either does not really have a purpose without the other. Prototypes are often used to find out user needs, test concepts and verify design. In industry, prototyping is used in rather late stages of the product development process, not always after concepts have been developed and user needs have been gathered. In this thesis, prototypes are used to aid in finding user needs and verifying made assumptions regarding product needs.

The objective of this thesis is to find out how prototype fidelity level effects on the usability evaluation of a product in development. To meet this objective, a novel metric was developed for defining prototype fidelity in relation to the time it takes to design and build. The research was done in the form of a case study of the design of a foot controller for a dental care unit.

Parametric prototypes of a proposed design for a foot controller were made at two fidelity levels, very low and medium and prototypes were tested evaluated by dentists who are the main target user of the final product. To keep the number of required tests to minimum, three parameters were selected for the prototypes to be varied at two levels. A L3 orthogonal array was used to minimize the number of combinations to be tested and Taguchi method was used in analysis to determine the optimal parameter combination based on evaluation.

The results suggest that very low fidelity prototypes can help in identifying usability issues and user needs as effectively as higher fidelity prototypes when developing a product. The evaluated low and high-fidelity prototypes received similar grades from evaluation, often averages were within 0,5 on a five-point scale. The use of very low fidelity prototypes during user interviews could help set the mood and bring up more thoughts in the customer testing the prototype. More thoughts about the product in turn would help in identifying user needs or usability issues which would otherwise stay latent.

Keywords Prototyping, prototype fidelity, Taguchi method, user need identification

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Prototyyppien rakentaminen on merkittävä osa mitä tahansa tuotekehitysprojektia, eikä kummallakaan varsinaisesti ole merkitystä ilman toista. Prototyyppejä käytetään usein käyttäjätarpeiden kartoittamiseen, konseptien testaamiseen sekä tehdyn suunnittelun validointiin. Teollisuudessa prototyyppejä käytetään melko myöhäisessä vaiheessa tuotekehitysprosessia, eikä useinkaan heti, kun konseptit on luotu ja käyttäjätarpeet kerätty. Tässä diplomityössä prototyyppejä käytetään käyttäjätarpeiden selvittämisessä apuna sekä tuotteeseen liittyvien tarpeiden varmentamisessa.

Diplomityön tavoitteena on selvittää, miten prototyypin fideliteetti eri tasoilla vaikuttaa tuotteen käytettävyyden arviointiin tuotekehityksen aikana. Jotta tämä tavoite saavutettaisiin, kehitettiin uudenlainen mittari prototyypin fideliteetin arvioimiseksi. Mittari suhteuttaa fideliteetin prototyypin rakentamiseen käytettyyn aikaan.

Ehdotetusta jalkapolkimen mallista tehtiin kahdella eri fideliteetin tasolla parametriset prototyypit, tasojen ollessa erittäin matala sekä keskitasoa. Prototyyppejä näytettiin lopputuotteen ensisijaisille käyttäjille, hammaslääkäreille, jotka testasivat ja arvioivat prototyyppien käytettävyyttä. Jotta rakennettavien mallien lukumäärä saatiin pysymään mahdollisimman pienenä, valittiin kolme haastattelujen ja kyselyn perusteella tärkeimmäksi koettua ominaisuutta, joita muutettiin kahdella tasolla. L3 ortogonaalimatriisin avulla minimoitiin testattavien yhdistelmien lukumäärä ja ihanteellinen parametrien yhdistelmä valittiin Taguchi-menetelmään perustuvan analyysin pohjalta.

Tulokset viittaavat siihen, että tuotekehityksessä erittäin alhaisen fideliteetin prototyypillä voidaan havaita käytettävyyteen liittyviä seikkoja yhtä tehokkaasti, kuin korkean fideliteetin prototyypeillä. Arvioidut alhaisen ja korkeamman fideliteetin prototyypit saivat samankaltaisia arvioita testauksessa, monesti erot arvosanojen keskiarvojen välillä olivat alle 0,5 viisiportaisella asteikolla. Alhaisen fideliteetin prototyyppejä voidaan hyödyntää asiakashaastatteluissa ja niiden avulla voidaan saada apua sopivan tunnelman luomiseksi haastattelutilanteeseen sekä tuomaan asiakkaan mieleen enemmän asioita. Useampi ajatus tuotteesta voi auttaa käytettävyyteen liittyvien seikkojen ja käyttäjätarpeiden sekä piilevien tarpeiden tunnistamisessa.

Avainsanat Prototyyppi, prototyypin fideliteetti, Taguchi menetelmä, käyttäjätarpeen tunnistaminen

Foreword

This thesis was motivated by the need to design a new foot controller for a dental care unit in development. The case study presented in this thesis is also part of the design process of the mentioned foot controller. The supervisor for this thesis was Prof. Katja Hölttä-Otto, who with great patience and knowledge guided my work with the thesis. The thesis advisor, my boss Tapani Kivelä MSc has trusted me in my work and given the freedom to make this thesis as I best see fit. I would like to thank my employer who gave me the opportunity to do this thesis by taking some time from working hours. Lastly and most importantly, I would like to thank my dear Sanna for supporting me through all of the ups and downs I had during the process. Without you, all of this would have been a dream.

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Johannes Niinikoski

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Abbreviations and markings

AC	Alternating current
DC	Direct current
UD	Universal design
DOE	Design of experiments
PFX	Prototype for X
MDD&A	Medical device development and assessment
$P_{(f)}5$	Fifth percentile female, refers to human dimensions, five per-cent of women are smaller than $P_{(f)}5$
$P_{(m)}95$	95th percentile man, refers to human dimensions, five percent of men are larger than $P_{(m)}95$
V	Volt

1 Introduction

Traditionally the product development process flow is such that as the time passes and expenses increase, so does the knowledge about the project. Also as decisions are made throughout the process, the chances of affecting on the end result decreases. Prototypes are the gemstones of a development process, as they make the intangible ideas a physical reality. Product development and prototyping can be seen as synonyms as neither really have a purpose without the other. With all of the possibilities prototyping offers, the quick and cheap type is the kind which offers cost effective and swift path to gather user feedback on concepts and ideas in development process, which is what this thesis explores.

1.1 Motivation and purpose

In the industry of dental care equipment, the devices are classified as medical devices and the design criteria and requirements enforced upon them are among the strictest ones for manufacturing industries. There are several design choices which come more or less directly from the standards but there are still plenty of choices to be made when developing the devices. The working environment can be demanding and the dental care professionals operating the dental care equipment can also be demanding about the equipment they use. As in many industries, the development cycle for a dental care unit is quite long and requires lots of resources. Once developed the device can be on the market for a long time and the equipment can be in use for decades. The development of the dental care unit is a massive task and it is best done by dividing the design process in to smaller tasks and entities. A foot controller is one of those smaller entities, which can be designed almost as a standalone module for the unit. Based on the intuition that the foot controller is more to a dentist than just a power controller of the instruments, this thesis strives to uncover the true meaning of a dental care unit foot controller to a dentist. Because the development of medical devices is strictly regulated, any design choice made is likely required to be justified one way or the other.

This thesis came from the need for a foot controller for a new dental care unit. As the development process of a new product is well known and several methods have been developed to manage the process, for this thesis novelty comes from studying the effects of prototype fidelity to usability evaluation and the idea of combining a method more commonly seen in quality engineering with traditional product development methods.

The purpose of this thesis is to support the development process of a new product and serve as a reference guide for future development projects. The driving force is in improving the current R&D procedures by introducing new methods, which emphasize on user centric design and systematic way of working.

1.2 Thesis objective

As this thesis is about product development and testing ideas in a systematic way and early stages of product development are an ideal time for quick and dirty prototyping and testing ideas, the research problem and thesis objectives were chosen to follow this theme.

The research problem of this thesis is, how very low fidelity prototypes could be used as effectively as higher fidelity prototypes in gathering user feedback and identifying the most desirable combination of feature parameters.

The thesis objective is to explore the effects of prototype fidelity on usability evaluation and how prototype fidelity effects on the feedback given by the user.

1.3 Scope and limitations of this thesis

The scope of this thesis is in early stages of product development process. The focus areas are prototyping with low fidelity prototypes and user centric design. Prototyping is introduced, how is it relevant to this thesis, what is prototype fidelity and how prototyping fits in the product development process. User centric design is introduced and identifying user needs and importance of customer involvement is discussed and explained how it is relevant to early stages of product development and prototyping. Also, principles of universal design are introduced to emphasize that in the development of dental care equipment. The design should ideally not only take into consideration the dentist ranging from fifth percentile female ($P_{(f)}5$) to 95^{th} percentile man ($P_{(m)}95$), but also those dentists with such temporary or permanent disabilities that does not prohibit them from working. They would benefit from a design that takes in consideration also those who are not in 100% working condition, not to mention the assistant or the patient that come in contact with the device.

This thesis is also meant to serve as information package for a R&D team, so some information will be introduced, which is not fully explored in the case study, but is relevant to an R&D project in general.

The idea of this thesis is to find out whether there is any difference in using low or high-fidelity prototypes in early stages of design process. In this thesis, it will be tested how Robust design method, an application of Taguchi method, could be used in the early stages development process of a dental care unit foot controller. Taguchi method was selected for analyzing the experiments because it is a robust and a simple method that enables to get results with minimal testing of different parameter combinations.

The limitations of this work are that only a light weight experiment has been executed to provide evidence for presented theory. Also, this thesis and the research is restricted only to early stages of product development process. No verification for the designed experiment will be provided in this thesis, so the results will provide only suggestive information. Also, because this thesis is done in parallel with development of an actual product, the prototypes will be used to test design ideas, which may have an effect on the results of the case study.

2 Literature review

The literature review introduces the key concepts and provides the theoretical framework for the case study. Product development is the process that combines resources and designers and through what often is a systematic, iterative way of working and results in a product for the market. An instrumental role in this process is not only with the design team but also embodiments of the ideas and concepts, the prototypes. Customers and product users are important stakeholders in the process as in the end the customer is the one who pays the cost of any development project.

2.1 Prototyping

Prototyping has a special meaning in product development. It is an integral part of the process giving ideas a shape and form and give a physical form to the concepts in product development. The purpose of prototyping may vary but all prototyping activity aims to advance the design process towards the finalized product in development. Prototyping will be discussed from the view point of what it is and what prototype fidelity is. Also, early stages of product development process will be introduced.

2.1.1 What is a prototype

Prototypes are some form of design that are made during the development process of a new product. They convey made decisions and the state of the design process. Prototypes can range from a sketch on a napkin to physical structures incorporating different levels of look, feel and function. (Buchenau, Suri 2000) Product development and prototyping are both an iterative process. Camburn et al. (2015) define iteration as the cycle of building, testing and improvement of a design concept. Iterations advance the design maturity in a systematic way. Prototypes can represent each iteration of the design.

The definition of a prototype is not necessarily self-explanatory as the tools and build material is not relevant. What matters is how the designer uses the item to demonstrate or explore some aspect of a product in development. Even something as ordinary as a pizza in a box can be a prototype for a laptop, if the designer wants to explore how an architect would carry it around a building site with all the other material they need to carry and do while at the site. In interdisciplinary teams, the term prototype can mean different things to members with different background. A shaped block of foam may be what an industrial designer calls a prototype, while a breadboard circuit is a prototype for the electrical engineer. (Houde, Hill 1997) A prototype needs a story or other mean to give it a meaningful context.

According to Houde and Hill (1997), a prototype can be defined as "*any representation of a design idea, regardless of medium".* The designer can be defined as anyone who makes a prototype to design something, regardless of qualifications or job title. There are two terms related to prototyping: resolution and fidelity. Houde and Hill (1997) also define resolution as the amount of detail a prototype has, while fidelity can be viewed as the closeness to the final design. What needs to be recognized is that the degree of the visual and functional readiness does not necessarily relate to the robustness of the design or a particular stage of the design process. What this means is that a visually refined prototype may be built at an early stage to sell the concept to the stakeholders and at a later stage a rough prototype is built to test functionality of the technology.

Houde and Hill (1997) categorize prototypes based on their purpose in the design process.

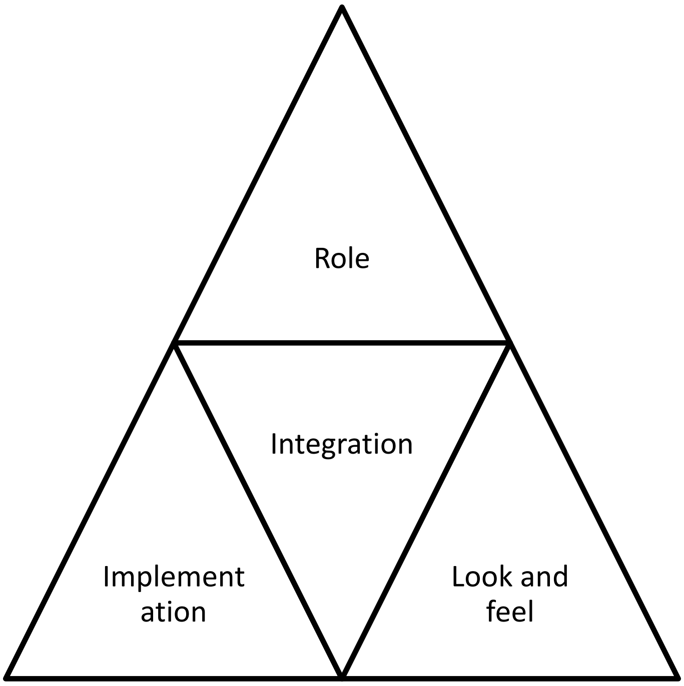


Figure 1: Prototype purpose in the design process (Houde, Hill 1997)

The presentation in Figure 1 highlights that no single dimension is more important than other and a prototype can have properties from multiple dimensions. The role of a prototype describes the function of the object in the lives of the customer. What role should it have in the lives of the potential customer and are the needed features of the object to support it? If the role is clear and the goal is to present the features of the object in a new way, then the focus of the prototype needs to be in the look and feel of the object. Look and feel relates to the physical properties of the prototype, how does it look, what does the user feel or hear while using the prototype. Now, if the functionality of the device bases on a new technology or an innovation, the prototyping effort should focus in the implementation of the features. Implementation describes how the prototype works, what techniques and materials have been used to make it. A prototype can explore any of these dimensions or even multiple of them. The relationship of the intended design to the dimensions can be expressed by placing a marker on the triangle. The marker helps to understand which dimensions are intended to be explored and which are not. Once all necessary information has been gathered by use of one or several prototypes, a final version, which integrates all the dimensions, can be created. (Houde, Hill 1997)

Ullman (2003) states that among other project deliverables, the progress of a design project is measured by prototypes, testing and the test results. During a development project, several models of the evolving product are made and while others are analytical models and simulations of some phenomena related to the product in development, others are the physical type, which are better known as prototypes. The models and prototypes represent the information that describes the product and *“design is the evolution of information punctuated by decisions.”* (Ullman 2003) Another approach is to classify prototypes based on the stage of the development process and characteristics the prototypes have which need to be taken in to consideration during the design process.

- Proof of concept prototype is used in the initial stages of the design process to help understand which approach to take during the design process. It has the purpose to serve as a learning tool and the function is to compare the customer requirements or the engineering specifications to the prototype functions. The proof of concept prototype can be constructed from any material, which is at hand as the material, manufacturing method or shape and esthetics are not important.
- Proof of product prototype is a physical embodiment of the product and helps further clarify the design. It is made to clarify and refine the components and assemblies and thus the manufacturing process and materials are important in the prototype.
- Proof of process prototype demonstrates that the material and production methods selected can successfully be used in a desired product. The manufacturing process and materials are the same or analogous as in the final product. These prototypes are made for functional testing and verification of the final design.
- Proof of production prototype can be used to demonstrate that the production process for the product is effective. The prototype is the first pre-manufacturing batch of the product ready for market. (Ullman 2003)

Prototypes can be viewed as learning opportunities for designers to understand and advance the core functions of the design at hand. (Menold, Jablokow et al. 2017) Research shows that more prototypes often result in technically better solutions as designers can identify problems and correct the design work accordingly. (Yang 2005, Camburn, Dunlap et al. 2015, Menold, Jablokow et al. 2017). Prototypes communicate the designers' ideas to partners, management, and customers. Prototypes are the objects that give shape to the work, which combines customer needs, product specifications and design team's ingenuity. (Houde, Hill 1997) Prototypes can also act as boundary objects among design team members and they help ensure that team members have similar conceptions about the design itself. (Menold, Jablokow et al. 2017)

Menold, Jablokow and Simpson propose a holistic prototyping framework to guide through the product development process and help the design team direct their efforts towards a prototype, which is useful and appropriate for a specific stage of the development process. This prototype for X framework could have a positive impact on the design outcome from the view point of desirability, feasibility, and viability of the final product. (Menold, Jablokow et al. 2017) The PFX framework contains three stages, Frame, Build and Test. Through the stages, PFX helps the designers to focus their efforts and resources towards building prototypes that test the core assumptions related to the design process. What is significant in the PFX framework, is that it takes into consideration the user centric approach, which other design frameworks fail to do. (Menold, Jablokow et al. 2017)

2.1.2 Fidelity

Prototype fidelity can be described as the level of realism at which the prototype describes the product in development. Prototyping is often a compromise of the time and resources available and the effort put in to achieve a certain fidelity level of the prototype. (Yang 2005)

Virzi (Virzi, Sokolov et al. 1996) defines prototype fidelity based on four dimensions, which are presented in Table 1.

Table 1: Four dimensions of prototype fidelity

Dimension	
Aestethic refinement	The aspects of the prototype that do not effect directly to the functionality of the prototype. Visuals of the prototype. How it looks and feels.
Breadth of features	The number of individual features the prototype supports. In addition, each of the features can vary in the degree of functionality.
Degree of functionality	The level at which an individual feature has the details complete.
Similarity of interaction	The way, how well a certain feature can be interacted with.

Prototype fidelity is not a straightforward thing to define precisely, but it is obvious to the user that a low fidelity prototype is such that compromises one or more of the dimensions. Low-fidelity prototypes may have a good degree of functionality for individual features and relatively complete breadth of features but they are lacking in the aesthetic refinement dimension. The similarity of interaction is often different in low-fidelity prototypes. In HCI context, low-fidelity prototypes are user interfaces on paper or similar. In physical product context, buttons can be just immobile protrusions or even drawn spots. (Virzi, Sokolov et al. 1996)

Low fidelity prototypes are often simple visualizations of the design ideas in development. They are used in early stages of the development process, because the time and resources required to build one are low. Low fidelity prototypes can be made from materials that differ from the final product. Such as paper, cardboard, plywood (Derboven, Roeck et al. 2010). High fidelity prototypes are more functional and interactive than low fidelity prototypes. They are built at later stages of the development process, and the materials and time to build them require more resources and generally they resemble the final product both functionally and visually. (Derboven, Roeck et al. 2010)

Virzi (1996) states that prototype fidelity may not be an issue, which needs to be thoroughly considered when building prototypes to represent an interface in a test, as long as a comparable functionality is maintained between the various prototypes. Also, a carefully constructed low-fidelity prototype is likely to reveal similar use related problems as when a high-fidelity prototype would be used. Camburn discusses the concept of relaxed requirements, which means that a prototype is intentionally constructed to meet only partially the functional requirements. Relaxed requirements are a form of low-fidelity prototyping with the difference that in low fidelity prototyping any aspect of the design can be relaxed. (Camburn, Dunlap et al. 2015)

Säde, Nieminen and Riihiaho (1998) have explored the use of low fidelity prototypes made from paper to test different concepts for a device that will be relatively complex as a finished product. The prototypes that were used in the research were defined to be low fidelity based on the categorization defined by Virzi et al. (Virzi, Sokolov et al. 1996). The prototypes were low fidelity in terms of aesthetics and functionality but similarity of interaction was very close to actual product. What the research reveals is that even with simple materials, a prototype can be fabricated quickly and it can be used to fulfill a specified task. In this case comparison of two different approaches to operating the product and identifying usability problems in them. (Säde, Nieminen et al. 1998) The terms prototype fidelity and usability often can be seen in relation to computer sciences when designing the user interface of an online service or a software application. The user interface of a computer program is simpler to test with a low fidelity prototype rather than making a fully functional program and alter it. (Walker, Takayama et al. 2002) The simplified user interface can also be implemented when prototyping physical products. A prime example of this is the study by Säde et al. (1998)

What is significant in low-fidelity prototypes, is that they are relatively fast to make and require low amount of resources. This means that several iterations can be made during the design process without much concern about the resources needed. The biggest portion of the resources in low-fidelity prototyping is taken by the time required from the design team. On the other hand, it can be argued that the use of high-fidelity prototypes takes even more time.

There is a correlation between prototype fidelity and the number of prototypes made during a development process. Less complexity allows for quicker prototyping and more testing of ideas during the design process (Camburn, Dunlap et al. 2015) Though, it is possible to identify usability issues regardless of prototype fidelity, but higher prototype fidelity increases the feeling of prototypes being closer to a finished product. (Boothe, Strawderman et al. 2013)

2.1.3 Product development process

Product development is a process that can be defined to have several stages, which consist of different tasks. Such tasks are understanding, creating, communicating, testing and persuasion. It can be generalized that any product development process consists of three phases:

1. Understanding the opportunity
2. Developing a concept
3. Implementation of the concept

Each phase contains all the activities that need to be addressed before moving to the next phase. It is noticeable that, the phases are intertwined and complex, and are not always clearly categorizable. Nevertheless, the categorization helps to understand and classify the process. First phase contains the activities that need to be completed before the decision to launch a product development effort can be made. Second phase contains the activities that need to be completed to make decisions about what the product will be. Final phase contains the activities that ensures that the product is ready for the market and manufacturing.(Otto, Wood 2001)

It is a known fact that majority of cost related commitments in development of a product are made in early stages of the development process. (Wheelwright, Clark 1992) What's integral in this is that the decisions made are difficult or impossible to change at later stages. The early stages of a development process provide the best opportunities to cut down on costs, improve quality, reduce cycle time, and build reliability into the product. This is also the time of the process when the developers know the least about the subject at hand, so the decisions made are relatively less informed than those made at later stages. What this implies is that most experimental effort should be put in to the concept and prototype stages of the development process. (Ellekjær, Bisgaard 1998)

It is important that before starting any development process, the product developers define carefully the project objectives on a precise level regarding product performance and manufacturing. By doing so, the team mindset is adjusted towards common goal. During initial stage of the development process is important to take time to gather input from potential customers and input from the potential manufacturing is important. Lack of customer input may result in a product that does not fit the customer need and lack of manufacturing input may result on a product too expensive to manufacture. Having the manufacturing input early in the design process reduces the chance that design changes are needed later during the design process. (Ellekjær, Bisgaard 1998)

Ulrich and Eppinger (2012) break down the product development process in to six stages: Planning, Concept design, Embodiment design, Detail design, Testing and Production. The phases that are in focus in this thesis are the Concept design and Embodiment design. Planning is called "*phase zero*" because it precedes project approval and actual launch of the development process. Planning phase begins with opportunity identification in relation to company strategy and includes the assessment of technology. In the end of the phase, the target market, business goals, key assumptions and constraints are known. This mission statement is where the actual development process can begin from. (Urlich, Eppinger 2012) Phase zero falls in the three-phase categorization in to understanding the opportunity.

"*Concept development*" is the first stage of the product development process. Here the needs of the potential users are identified and alternative concepts are generated and evaluated. One or more concepts are selected based on the evaluation for further development and testing. A concept is the description of the function, features and form of the product that are accompanied by a set of specifications and an analysis of a competitive products. (Urlich, Eppinger 2012) Concept development falls in to the second phase in the three-phase categorization.

The decision to bring experimentation in the form of prototypes in the early stages of product development could help in planning and concept development as information could be gathered through multiple means. The main benefits of the use of experimental product development are simultaneous optimization of several factors and simultaneous cost reduction and quality improvement. Also, the developed product can be made robust to any uncontrollable factors either in the product itself or operating environment. Lastly the systematic process of problem solving can help designers stay on planned course and not get lost in trying to get a grip on uncontrollable variables. (Ellekjær, Bisgaard 1998)

2.2 User centric design

Taking users and their needs in to consideration, when designing any product, is all the time more important. Competition is tough and companies need to justify to potential customers increasingly more, why they should purchase your products. A good justification is to be able to say that customers have had their opinions heard in the development process. Taking customers into any product development process is likely to bring a competitive edge for the product.

To meet the expectations of customers' in designing and manufacturing any product, is a complex task. The combination of multiple parameters affecting the result makes the process difficult and moreover, the interrelationships, which are often complex, are not well documented. What this leads to is in uncertainties about the future performance of the product that could result in reliability issues or other quality problems. The designers need to make decisions regarding product specifications regardless of these interrelations and while some may be known from past experiences, some will always be found only through experimentation. (Ellekjær, Bisgaard 1998)

According to Kaulio (1998), user-oriented or user centric product development is a human factors approach to product design and is characterized by three features:

- Problem analysis with user requirements with use scenario as the starting point and resulting in the formation of user requirements
- Transformation of user requirements to measurable engineering requirements
- Iterative design process where prototypes are tested by users and modified by designers.

Customer involvement in product development can be divided into three categories: design for, design with and design by.

The design for defines customer involvement as object-like, from which the design criteria are extracted out of. Customer involvement is limited to beginning stage of the design process where the customer needs are gathered and transformed into product performance and design requirements.(Kaulio 1998)

The design with defines customer involvement as more integral to the design process. Customer feedback is gathered throughout the design process on prototypes and this way the design process is more iterative. The difference in different design stages are related to product readiness and use context. User-centric design is related to this category of customer involvement and methods such as concept testing and beta testing are methods that are used in this category.(Kaulio 1998)

The design by category defines customer involvement as more of a partnership -like relationship in which the distinction between designer and customer ceases to exist. Instead of just expressing their needs and experienced problems, customers take an active role in the design process and the selection of various design solutions. The role of the designer changes to one of a facilitator who enhances the customers' chances to find a solution to their problem. (Kaulio 1998)

According to Hyysalo (2006), there is a considerable difference between making improvements to a product and identifying and capitalizing on the knowledge, which is essential to the future of the technology. There may be the situation that active collaboration with product users is fundamentally fragile in the company. More established priorities may dismiss the activity. As Hyysalo states it; "*gaining high quality input form users is not self evindent, requires "gardening" and can be effectively undermined*."

Hyysalo has identified dynamics of learning that describe the processes that are typically reported as learning, preconditions for learning and the management of conflicting learning goals. (Hyysalo 2006) Technical shortcomings become visible and diagnosable when the device is implemented in actual context of use. The most relevant dynamics in the context of this thesis are:

The first dynamic of learning is about technical problems in hardware and software in field use. Software issues and hardware problems become visible and diagnosable when devices are implemented in actual use context. This requires that the involved engineers go to the site, look at the problems and return to laboratory to make necessary adjustments and return to the field again. (Hyysalo 2006)

The third dynamic of learning is about unlearning existing assumptions related to the product and its use. This is related to the perquisites of further learning. The designers shift their mindset from assuming, that deviations from expected is relevant to question the frame within that they diagnose the problems. The key is not to assume but rather think about the roles of the designers and users in gathering information about problems and the purpose of the designers to users. (Hyysalo 2006)

The sixth dynamic is about the artifact acting as an expanding boundary object. As the learning and interaction is significantly dependent on the tools and means available, the most important item for mediating between users and designers is the product in development. Over time as collaboration increases, the shared area of the object expands. This means that the extent of interaction grows and more systematic uses of the boundary object emerges. (Hyysalo 2006)

Learning-by-using is an important interaction mechanism in development of new technology. The development process does not stop in the launch of a product and the postlaunch learning between designers and users is something that needs certain preconditions to be met for it to work properly. Learning for interaction is needed to create necessary preconditions for beneficial interaction and learning. Also learning in interaction is an integral part of the interaction that consists of the processes of acquiring information about identifies issues. (Hyysalo 2006)

For a product developer, it should be obvious that just asking users about their needs regarding the features or use of a product is insufficient. As users likely fail to verbally express their needs or preferences, more interactive methods to interact with current or potential users can be used instead or alongside more traditional research methods such as surveys or interviews. (Heiskanen, Hyysalo et al. 2010)

Heiskanen et al. (Heiskanen, Hyysalo et al. 2010) argue *"that experience and interaction are not simply outcomes of 'mixing the right ingredients', but contextual and dynamic process."*

2.2.1 Identifying user needs and taking them into development

Identifying the needs of the customer can be a tedious task that has several issues bound together. Otto and Wood (2001) point out of the most profound issues: The customer needs to understand what is being developed. How this is typically done is that the customer is showed a similar existing product and using it to help find the customer preferences of the product. The underlying issue with this is that the product showed is not the same one which is under development and the issue is highlighted with products under development with features that do not exist yet. The customer often identifies only the shortcomings of an existing products and it may require probing from the designer to be able to identify the latent needs, which the customer does not directly express. (Otto, Wood 2001) The difficulty of this task can be also graphically expressed with Kano diagram in Figure 2. This expresses the relationship between customer satisfaction and any feature of the product.

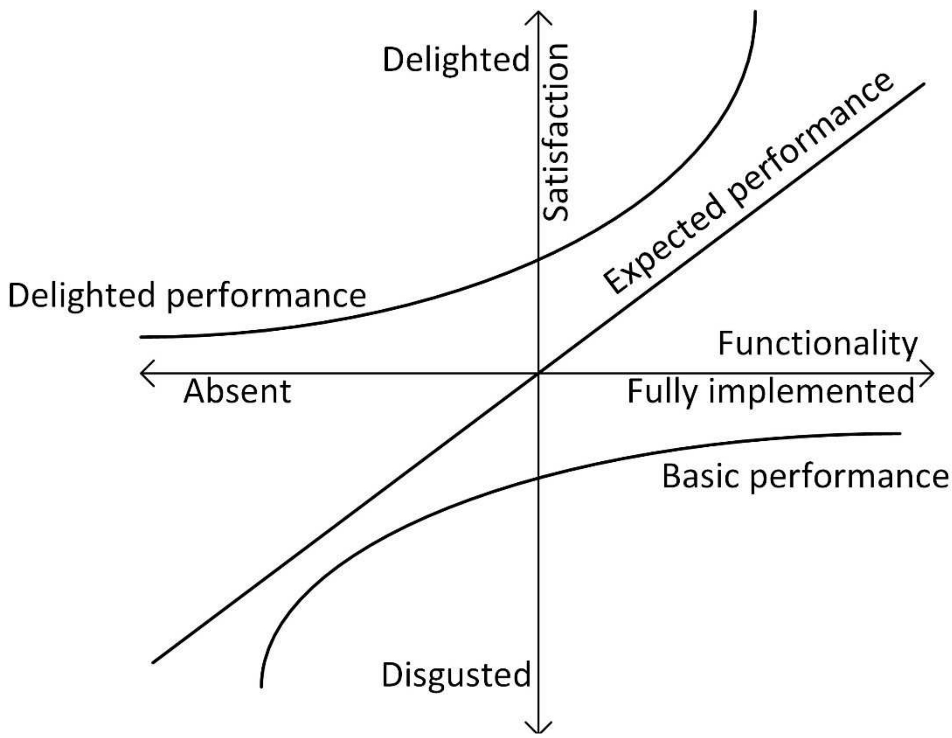


Figure 2: Kano diagram of customer satisfaction (Shiba, Graham et al. 1993)

The Kano diagram (Shiba, Graham et al. 1993) describes customer satisfaction on a scale from disgusted to delighted. The product has features, which may be absent or fully implemented, depending on the readiness of the product. Now if product performs as one could expect in relation to the customer need, the satisfaction plots as a 45° line. This is known as the expected performance curve, which indicates the nominal satisfaction level for any level of functionality in the product.

The minimum level of satisfaction, the customer could expect can be expressed with the basic performance curve. If basic performance is not met, the customer satisfaction will decline severely. The performance level that should be the goal is the performance that matches the delighted curve. The product functions are implemented on a level that exceeds customer expectations and they are delighted for it. What is profound in the diagram, is that as features are added to products and they become more common, the customer expectations shift and over time what previously matched the delighted satisfaction becomes the expected. Keeping in touch with customers to understand their current needs is therefore vital. (Otto, Wood 2001)

Customer needs can be categorized based on how easily they can be expressed and how quickly they change over time. Otto and Wood have proposed the following categorization showed in Table 2:

Table 2: Types of customer needs (Otto, Wood 2001)

CUSTOMER NEEDS	
DIRECT NEEDS	Needs, which are easily recognized. The customer can identify them and express them directly upon asking.
LATENT NEEDS	Needs, which the customer is not able to express directly upon asking but exist regarding the product or the use of the product. Latent needs may not be directly related to product features but the way it is used.
CONSTANT NEEDS	Needs, which exist always the product is used. They will always need to be filled when the product is used.
VARIABLE NEEDS	Needs, which may change over time or disappear because of foreseeable technology development. Since the customer may not understand these needs, it may be difficult to get an understanding of them through discussions with the customer.
GENERAL NEEDS	Needs, which apply to everyone in the potential customer base.
NICHE NEEDS	Needs, which require to be filled for only a small portion of the potential customer base.

The needs are in three categories and what causes the boundaries of the customer needs to change is the state of technology and the rate it changes. First category, direct vs. latent needs, considers how the needs can be observed. The second category, constant vs. variable needs considers how technology change effects the needs. The last category, general vs. niche needs, considers how vastly a certain group within the potential customer base be satisfied by fulfilling a need. As pointed out, it is a different task to attempt to fulfill a need that applies to whole customer base than a small “niche” group.(Otto, Wood 2001)

Identifying customer needs can be described as a five-step method. The light structure of the method should be viewed more like a starting point for continuous development and refinement, facilitates effective product development practices. (Urlich, Eppinger 2012) The five steps are:

1. Gather data from customers
2. Interpret the raw data in terms of customer needs
3. Organize needs into a hierarchy of primary and secondary needs
4. Establish the relative importance of the needs
5. Reflect on the results and the process

For data gathering, there are many options available, but three of the most common methods are interviews, focus groups and observing the use of a product. When performing an interview, the design team member discusses with a single customer, often in the environment the customer uses the product. Customers responses are recorded for further analysis. Questionnaires are a list of questions, which are relevant to the customer, the use of the product. Focus groups are facilitated sessions with a group of customers. Typically, the focus group is held in the design team's environment and there is some way to observe the customers actions during the focus group. (Otto, Wood 2001)

Customer needs are expressed as written statements after the raw data has been gathered from customers and interpreted. After steps 1 and 2 there should be a list of 50 to 300 customer needs, which can be cumbersome to work with. Therefore, they are needed to be organized in to a hierarchical list, which typically consists of primary and secondary needs. (Urlich, Eppinger 2012) Once the needs are in a hierarchical order, the relative importance between them needs to be established. This can be done in two ways, either the development team can rely on a consensus of the team members based on their experience with customers or a customer survey can be done to base the importance of assessment on customer feedback. There are trade-offs between speed and accuracy when using on or the other of the methods. (Urlich, Eppinger 2012)

When the customer needs have been interpreted and a customer interview does not provide new statements, the gathered information is compiled in to a list of customer needs for the new product. A simple way to do this is to sort the customer needs based on affinities among the needs. The method is known as affinity diagram method. The traditional way is to write each need to a card and attach them on a large board or wall, where you can see them all at once. (Otto, Wood 2001) The work flow is the following:

1. Attach first need on wall.
2. Compare next need to first, if the second statement is basically the same as the first, the card is attached below the first to form a column. If they differ, the second card is attached next to the first card.
3. Next card is compared to the ones on the wall and step two is repeated until all needs have been sorted.

Once all cards are on the wall, the result is a grouping of customer needs, which reflects the customer demands, desired and their relative importance to each other. The sorted categories of needs can be labeled under a more generic name but it is not an optimal solution as the original meaning of the customer need may change. On the other hand, the affinity diagram method is relatively effective and simple to implement. (Otto, Wood 2001)

The final step is to reflect on the results of the customer need identification process and the results. The process is not an exact science and therefore the team must challenge the gathered results to verify that they are consistent with the intuition and knowledge within the team. (Urlich, Eppinger 2012)

When developing medical devices, it is relevant to acknowledge that medical device users are a heterogenous group and their working environment, skills and needs may differ significantly. In medical device development and assessment (MDD&A) the involvement of the device users in development and assessment is vital as the medical device users are one of the key stakeholders in medical device technology. (Syed Ghulam, Robinson 2006)

In development of medical devices, typical methods in capturing user perspectives at a particular design stage are: interviews, usability tests, questionnaire surveys, user and producer seminars, task analysis, discussions and observations. In addition, in concept stage simulations and user feedback can be used. At design stage simulations, human factors approach and design sessions are used. (Syed Ghulam, Robinson 2006)

Kaulio (1998) has identified three main interfaces for user involvement, which are specification, concept development and prototyping as part of product development process. According to Syed Ghulam & Robinsson (Syed Ghulam, Robinson 2006) the user involvement in medical device technology development occurs also in testing, trials, and deployment stages of the design process. User involvement in early stages of the design process is important as it can benefit the developers and users of the product and helps adopting user needs. If the highest user involvement is in the design process, it helps to create medical devices, which have higher usability for the users. (Syed Ghulam, Robinson 2006) Combining various methods for customer involvement is important in development of medical device technology as involvement of different types of users and understanding their needs and perspectives on the device use can’t be achieved with the use of a single method. (Syed Ghulam, Robinson 2006)

2.2.2 Principles of universal design

The term universal design (UD) is used to describe the process of designing any product or operating environment to be usable all possible users and age and ability. Although the goal of universal design is to integrate people with disabilities to the social environment and improve device accessibility for them, it can also be used to improve usability for any user of a device. Universal design is important also because device accessibility and usability of the medical equipment can influence on the quality of health care provided. Universal design aims to fit the needs of all users regardless of physical features, age, skills, or disabilities. Although this results in requirements, which are difficult to achieve, they are still worth striving for (Follette Story 2007)

The Center for Universal Design has published the Principles of Universal Design (Table 3). Each principle is followed by a set of guidelines used to describe the key elements, which should be present in any design which follows the principles.

Table 3: The Principles of Universal Design and their definitions (Connell, Jones et al. 1997)

Principle	*Purpose*
Equitable use	The design is useful and marketable to people with diverse abilities
Flexibility in use	The design accommodates a wide range of individual preferences and abilities
Simple and intuitive to use	Use of the design is easy to understand, regardless of the user's experience, knowledge, language skills, or current concentration level
Perceptible information	The design communicates necessary information effectively to the user, regardless of ambient conditions or the user's sensory abilities
Tolerance for error	The design minimizes hazards and the adverse consequences of accidental or unintended actions
Low physical effort	The design can be used efficiently and comfortably and with a minimum of fatigue
Size and space for approach and use	Appropriate size and space is provided for approach, reach, manipulation, and use regardless of user's body size, posture, or mobility

The purpose of UD and the guidelines was to communicate the concept of the principles in an easily understood way. The principles are meant to guide the design process and allow a systematic approach to evaluation of designs. In designing medical equipment, UD has deeper importance because of the diverse people using the equipment and how the design of medical equipment can have a substantial effect on the efficiency and safety of the people using the devices. (Follette Story 2007)

The guidelines associated with the principles and examples in health care and dentistry are expressed in Table 4 through Table 10:

Table 4: PRINCIPLE ONE: Equitable Use

Guidelines	
Provide the same means of use for all users	Identical whenever possible; equivalent when not. The chair control panel for the dentist and assistant side are implemented the similarly on touch screen and keyboard.
Avoid segregating or stigmatizing any users	Apply ergonomic recommendations to fit design for a wide user group. Identify the needs of special users and figure out how they can be taken in consideration in the design.
Provisions for privacy, security, and safety should be equally available to all users	Incorporate safety measures to prevent harm from for example, moving components.

Make the design appealing to all users	Designing medical devices to be attractive in addition to being functional, will appeal to a larger number of potential users (Follette Story 2007)

Table 5: PRINCIPLE TWO: Flexibility in Use

Guidelines	
Provide choice in methods of use.	A dental chair with adjustable back and foot rest can accommodate non-average body shapes and position preferences of the dental care unit operator. (Follette Story 2007) Chair control can be implemented on foot controller, instrument bridge and assistant side.
Accommodate right- or left-handed access and use	Devices, which are symmetrical about access direction, may be used ambidextrous. (Follette Story 2007) Control panels, instrument bridges and similar components can also be designed to be moved from one side to another to enable ambidextrous use. Power control of foot controller is designed symmetric for left and right foot use.
Facilitate the user's accuracy and precision.	Color and shape coding as visual clue to enable correct connections between medical device components. (Follette Story 2007) Also color, shape and size should be used in the design of controls for a medical device, for example foot controller.
Provide adaptability to the user's pace.	The skill level of the personnel using medical devices can vary. Some are beginners and need time to learn to operate the device while others are experts and adapt the use of a device quickly. Medical devices should accommodate the entire range of user proficiency. (Follette Story 2007)

Table 6: PRINCIPLE THREE: Simple and Intuitive Use

Guidelines	
Eliminate unnecessary complexity	Medical devices should be as simple as possible without omitting required functions. Often used functions should be available immediately and less frequently used functions may be located in a menu of a control panel and accessed only when needed. (Follette Story 2007)
Be consistent with user expectations and intuition	The use of standardized symbols, generally accepted component arrangements and color codes will make the device easier and faster to learn and operate. (Follette Story 2007)
Accommodate a wide range of literacy and language skills	The use of icons and color coding is preferred over textual communication. (Follette Story 2007) Also minimizing or omitting any text will mitigate the possible issues related to accuracy of multilingual translations.
Arrange information consistent with its importance	Most frequently used components such as buttons on a foot controller should be easily recognized and located regardless of operating scenario. (Follette Story 2007)

	Design power controller and buttons on foot controller in a way that they can be found feeling by foot.
Provide effective prompting and feedback during and after task completion	Audible signals or flashing signal lamp to indicate a flushing sequence of the instruments has ended or the curing sequence of the curing light is in progress or has finished.

Table 7: PRINCIPLE FOUR: Perceptible Information

Guidelines	
Use different modes (pictorial, verbal, tactile) for redundant presentation of essential information.	Medical devices that have visual output could also have audible output. (Follette Story 2007) For example, dental turbine water on/off toggle.
Provide adequate contrast between essential information and its surroundings	Minimize the amount of different colors in one symbol and ensure that the contrast between different symbols and the background is strong. (Follette Story 2007)
Maximize "legibility" of essential information	Audible output should have volume control and visual displays could offer choice of different color schemer or fonts for example. (Follette Story 2007)
Differentiate elements in ways that can be described (i.e., make it easy to give instructions or directions)	Written and oral instructions are easier to give when components of the medical device clearly differ from each other. (Follette Story 2007) In dental care equipment, user serviceable parts could be highlighted with a completely different color than rest of the unit.
Provide compatibility with a variety of techniques or devices used by people with sensory limitations.	Separate and mark for example standby and error lights, instead of using a single bi-color signal lamp. Use visual and audible signals.

Table 8: PRINCIPLE FIVE: Tolerance for Error

Guidelines	
Arrange elements to minimize hazards and errors: most used elements, most accessible; hazardous elements eliminated, isolated, or shielded.	Hazardous elements should be eliminated from medical devices whenever possible. If not, they should be located in areas where the user typically does not access. (Follette Story 2007)
Provide warnings of hazards and errors	Color coding hazardous elements could make it faster to recognize them. (Follette Story 2007)
Provide fail safe features	Add a safety cable to prevent a total collapse of chair back rest.
Discourage unconscious action in tasks that require vigilance	Medical devices may require multiple or simultaneous steps in a sequence in order to ensure that the user is paying attention during critical tasks. (Follette Story 2007)

Table 9: PRINCIPLE SIX: Low Physical Effort

Guidelines	
Allow user to maintain a neutral body position	Handles on carts should be in vertical position rather than horizontal to prevent prolonged forearm pronation. The handles should be long enough that people of varying height can grasp them at the location most comfortable to them. (Follette Story 2007)
Use reasonable operating forces	Use smallest possible counter force on foot controller power control element to provide a returning force for neutral position.
Minimize repetitive actions	Instead of having to constantly set the unit chair to operating and patient loading/exit position, add a memory function to automatically set the chair in correct position.
Minimize sustained physical effort	Design the instrument cable retaining whip arms in a way that the operator does not need to pull on the instrument

Table 10: PRINCIPLE SEVEN: Size and Space for Approach and Use

Guidelines	
Provide a clear line of sight to important elements for any seated or standing user	Implement a display that provides information to the dentists while they are working in patients' mouth.
Make reach to all components comfortable for any seated or standing user	Design movement range of dental care unit components in a manner, which enables dentists to work in any preferred position.
Accommodate variations in hand and grip size	Provide different sized handles and grips for operators to select from.
Provide adequate space for the use of assistive devices or personal assistance	Design patient chair to be moveable so patients in bed or wheel chair can be treated.

Follette Story recommends that medical device manufacturers test new designs with a wide variety of potential users during the development process. Testing should occur early and often to ensure the efficient use of test user feedback. (Follette Story 2007) What this means is that incorporating the means of user centric design and having users participating in the design process early on, can have a positive impact in the successful incorporation of the principles of universal design.

2.3 Ergonomics and medical device standards

There are ergonomic requirements for the foot controller. The standards such as EN 60601-1 do not set requirements regarding ergonomic use beyond the statements such as the foot controller must be designed and labeled in a way that the use of the foot controller does not result in an unacceptable risk. However, dental ergonomics experts, like Hokwerda et al. (2006) have compiled a list of requirements to ensure ergonomic use of the foot controller for dentist ranging from a $P_{(f)}5$ to $P_{(m)}95$ dentist. The design requirements for a dental care unit foot controller are listed in Table 11. The basis for the requirements are several ergonomic related standards, directives and literature regarding ergonomics in general and dentistry work. Their goal has been to define a functional man-machine system for dentists to operate. (Hokwerda, Wouters et al. 2006)

One of the reasons, why it is important to focus on creating an ergonomically good product is that 65% or 2 out of 3 dentists have musculoskeletal complaints to a varying degree of severity and symptoms can be: hindrance in function, loss of working time, pain, or discomfort. There is a considerable risk of partial or permanent disability resulting from mental and physical factors. The problematic issue is that muscle tension increases in relation to stress and the physical load on dentists is regularly already high. What also noticeable is that there are more women entering the field of dentistry and they are more prone to develop musculoskeletal pain than men. (Hokwerda, Wouters et al. 2006)

The ergonomic requirements were created because of the frequency of musculoskeletal problems and disabilities dentists experience due to ergonomic limitations of their dental equipment. Also, current legislation and standards dictate that equipment must be available that can be operated without damaging the operators' health, but little else is given as design guideline. Finally, the equipment is more often bought by members of organization administration for other users than themselves. (Hokwerda, Wouters et al. 2006)

Table 11: Design requirements for ergonomic foot controller

Heel movement	The heel should stay on floor to support the foot, while the front part is placed on the pedal. While doing this, the foot should be raised from the heel by an angle between 5° and 15°
Power control pedal length	Length of the pedal should be max 22cm. Because the foot is not fully placed on to the pedal, a shorter length is preferred
Power control pedal width	The width of the pedal should be max. 12.7 cm. In practice, narrower will be sufficient so 7cm is accepted
Power control pedal design	A foot controller may be designed so that the pedal is operated by pressing on the side by movements to left or right.
Power control pedal design	Preference to this mode of operation must be given, because the heel rests on floor and small movements of max 15°, which require little strength are needed
Power control pedal design	A combination exists where the pedal is set to a certain position in relation to desired speed and instrument is activated by pressing the pedal.
Moving the foot controller	The support for moving the foot control with the foot should be 8cm high and 13cm wide. Taller is not accepted because a $P_{(m)}95$ dentist would have to lift their foot too high. A half open support works differently with left and right foot and therefor is less advised.
Mass	The weight of the foot controller should be such that it can be easily repositioned without the controller sliding

	away. If the foot controller is light, non-slip material should be attached to the base.
Number of functions	The foot controller should be designed as simple as possible with minimal functions to operate it. Different functions should be identifiable by recognizable colors and symbols.
Number of functions	Due to hygiene reasons, more functions are added to be operated via foot controller. This should not be in the expense of practicability particularly because the foot controller is not visible during treatment.

These requirements benefit the designers of dental care equipment and enables them to meet the standards and legislation for use of the equipment without causing harm to the operator. (Hokwerda, Wouters et al. 2006)

On a more general level, Tilley (2002) states that a product design should fit all users between a 99-percentile man and 1-percentile woman. The motion ranges of the leg and foot are such that comfortable motions for ankle rotation are between 0° and 21° down when neutral position is 90° between bottom of foot and shin. On the other hand, in a sitting position comfortable motion range for knee twist is approx. 15° inward and 20° outward twist when neutral position is when the foot is parallel to thigh.

User needs and ergonomic requirements are not the only things effecting the design specification for a dental care unit foot controller. Standards such as EN 60601-1 dictate several aspects of a foot controller design. The standard contains requirements for both mechanical and electrical safety and usability.

The standard dictates durability and operational safety related items. There are several standards that apply or could be applicable, depending on the design choices such as, the fidelity level of electronics used in the foot controller. Also, not all applicable standards are directly stated as some may become applicable based on a design choice such as selected material or device dimensions. As it would become very complex to discuss about all the standards, which could apply and the restrictions they may cause on the design, only some examples related to the mechanics, electronics and usability of the foot controller will be introduced here. As standards are constantly updated, the following should be viewed as a reference with reservations. Some of the requirements dictated by standards are listed in Table 12.

Table 12: Requirements for dental care unit foot controller as per standards

Standard and clause	*Requirement*
EN 60601-1 15.4.7.1 b) Mechanical strength	The foot controller should withstand the weight of a human standing on top of its enclosure. The testing is done by applying a force of 1350N for 1 minute, over an area of 30 mm diameter.
EN 60601-1 9.4.1 Instability hazards: general	The me equipment other than fixed equipment, intended to be placed on a smooth surface such as a floor, shall not overbalance or move unexpectedly, to the degree that it could present an unacceptable risk to the patient or operator.

EN 60601-1 9.3 Hazard associated with surfaces, corners and edges	There should not be any sharp or burred edges or corners, which may cause an unacceptable risk. The attention must be paid to flanges, frame edges and removal of burrs.
EN 60601-1 15.4.7.3 Entry of liquids	The foot controller should pass the fluid ingress test done according to EN 60529, class IPX1
EN 60601-1 15.4.7.2 Accidental operation of me equipment	The foot controller should not actuate any instrument or function unintentionally if tipped over
EN 60601-1 7.1.1 Usability of the identification, marking and documents	The usability engineering process needs to address the risk of poor usability regarding the design of the identification, marking and documents of the foot controller.
EN 60601-1 8.10.4.1 Limitation of operating voltages	If the foot controller is connected to the dental care unit by a cable, the operating voltage limited to 42.4V peak AC and 60V DC.
EN 60601-1 8.10.4.2 Connection cords	The connection and anchorage of the cable has is required to meet requirements specified in 8.11.3, if the breaking free or shorting of the conductors result in a hazardous situation.
EN 60601-1 12.1 Accuracy of controls and instruments	Whenever applicable, the manufacturer shall address the risks associated with accuracy of controls and instruments.
EN 60601-1 9.2.2.2 Gaps	A trapping zone is not considered to be present if the gaps of trapping zone comply with dimensions specified in table 20. This means that gaps and holes on the foot controller must comply with ISO 13852:1996

2.4 Robust design method

Robust methods, which are also known as Taguchi methods, are a set of statistical design methods developed by Genichi Taguchi to improve the quality in manufacturing and product development. The traditional process of improvement of objective parameters is known as design of experiments (DOE). There are two purposes for DOE: 1) explore effects of the objective parameters and improve them by adjusting. 2) Explore effects of output and do tolerance design. Robust methods such as Taguchi method are used in quality engineering and product development. The focus in Taguchi methods is improvement of quality and maximizing profit. It is based on three procedures: 1) orthogonal array, 2) S/N ratio, 3) loss function. The use of mentioned tools is not robust design as such, since they are used to evaluate products and technical solutions. (Taguchi, Chowdhury et al. 2005)

Taguchi methods focus on quality defined somewhat differently from the traditional product conformance to specifications. Taguchi defines quality in a way that it is related to loss of currency, not only for the manufacturer, but customers and the society as a whole. Quality is defined as *“the loss imparted by the product to the society from the time the product is shipped”.* The quality loss function has been created to evaluate the loss caused by functional variation of a product and the functions are presented in Table 13. Depending on what is the target point to achieve, there are three versions of the quality loss function that can be used:

nominal-the-best, smaller-the-better and larger-the better. The nominal-the-best is used when there is a known target to hit and there is an upper and lower limit. Such example is dimensions of a cast part. Smaller-the-better is used when the target is zero. Such example is wear of a component. Larger-the-better is used when target is infinity. Such example is fuel efficiency. (Taguchi, Chowdhury et al. 2005)

The way the quality loss functions work is that they treat off-target values as noise. The further away the output value is from the target, the larger is the MSD and thus the S/N ratio is smaller. (Ullman 2003)

The orthogonal array is a special tool used in Taguchi method. The reason, orthogonal array is regarded as a special tool in Taguchi methods, is because it can evaluate the reproducibility of functionality for customer conditions. Also, it deals with the difference equation calculations. (Taguchi, Chowdhury et al. 2005)

Table 13: Formulae for the quality loss function

Quality loss function	*Mean square deviation (MSD)*	*S/N ratio*
Smaller-the-better	$\frac{1}{n}\sum_{i=1}^{n} {y_i}^2$	$-10\log\left(\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right)$
Larger-the-better	$\frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{{y_i}^2}\right)$	$-10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2}\right)$
Nominal-the-best	$\frac{1}{n}\sum_{i=1}^{n}(y_i-\bar{y})^2+(\bar{y}-m)^2$	$-10\log\frac{1}{n}\sum_{i=1}^{n}(y_i-\bar{y})^2$

Taguchi et al. (2005) describe the typical working order for a product design as follows: the specification and drawings for a production version is made right after the prototype functions under certain conditions. The functionality of the product is not studied any further until problems start to show up in customer use. Now, after problems have emerged, the product is tuned adjusted or redesigned to fix the found issues. The process described is called firefighting and is needed when robust design has not been done. (Taguchi, Chowdhury et al. 2005)

Robust design provides a systematic approach to finding optimum values for design factors. The aim is to find values that result in economical design and low variability in product. Taguchi method can be used to achieve these goals. The first step after system design has been done is to perform parameter design and if results are not optimal, tolerance design can be performed. (Taguchi, Chowdhury et al. 2005)

Parameter design is the process of identifying design parameters or process settings that affect the variability of the product. The design is a two-stage process, where control factors are identified first and signal factors are identified second. The control factors are design parameters, which are affected primarily by the S/N ratio but not the mean. With statistical planned experiment, the level of control factors can be identified at which the product variability is minimal. Once the variability has been minimized, mean response can be adjusted by performing the experiment and adjusting the signal factors. (Taguchi, Chowdhury et al. 2005)

Taguchi method offers two paradigms for engineering design:
1. Robustness comes first and then adjusting the average
2. When improving quality, parameter design comes first and then tolerance design

The distinctive feature with Taguchi method is that it uses SN ratio as measure of quality. It is the ratio of the power of the signal to the power of the noise. The scale is expressed with the unit decibel (dB). The higher the value, the better the SN ratio. The SN ratio in parameter design gives the interactions between a signal factor, control factor and the noise factors. (Taguchi, Chowdhury et al. 2005)

Taguchi (Taguchi, Chowdhury et al. 2005) explains that in quality engineering, the two primary uses of parameter design are the introduction of the SN ratio to measure functionality and the use of orthogonal arrays to find out the level of interactions between the control factors. If interactions exist, the reproduction of the conclusions may be questionable. What the SN ratio does, it shows interactions between the control, signal, and noise factors. It helps to avoid interactions between control factors but it is not known just based on the SN ratio whether the interactions are significant if they exist. For this reason, orthogonal arrays are used to check for interactions. (Taguchi, Chowdhury et al. 2005)

In traditional design of experiments, errors are assumed to be random and distribution is taken in to consideration. Also, there is no distinction between noise and control factors. This is where the quality engineering approach by Taguchi (Taguchi, Chowdhury et al. 2005) differs from the traditional design of experiments. As the experiments are often conducted in laboratory conditions, it is imperative that the conclusions are reproducible in the real world. In this case reproducibility does not mean that the results of the laboratory experiment can be reproduced under the same conditions again, but rather in the following situations:

1. The conclusions made with the test sample can be reproduced with a sample from actual product.
2. The conclusions made from small scale manufacturing can be reproduced during large scale manufacturing.
3. The conclusions made under limited conditions can be reproduced in various customer use conditions.

The laboratory conditions differ from those conditions the product meets in manufacturing and customer use and because of this the response differs in these conditions from the output response of the laboratory conditions. For this reason, the differences need to be adjusted to have the output hit the target. The second phase of a two-step optimization happens here. At first stage, only functionality is improved. (Taguchi, Chowdhury et al. 2005) The Taguchi methods are a set of powerful tools and implementing them in product development has the potential to improve the process efficiency dramatically.

2.5 Foot controller

Little information on foot controllers can be found on the market. One explanatory reason could be the fact that manufacturers supply their foot controller as a part of the unit and the foot controllers are proprietary equipment. Thus, it is not possible to operate one manufacturers unit with another's foot controller. There are a few manufacturers, which manufacture a generic foot controller that any manufacturer can implement to their units, but publicly available information is scarce and what can be found, provides a general overview of a product but nothing much in detail. Due to the convenient timing, a field survey to IDS (International Dental Show), one of the world's largest dental expos, was done to find out what kind of foot controllers are out there and what is the current state of art.

Based on over 50 different models observed, the foot controllers can be categorized to 5 categories based on the actuator meant to control the power of the instrument selected. Based on the observations made, the ergonomic properties and usability of each controller type can vary relative to the design of a controller and the size and working habits of the dentist. It seems to be difficult to find a categorization of dental care foot controllers based on their control concepts. One study on foot controller ergonomics defines the types of foot controllers tested in the study (Gerhard 2011) and this categorization is appended from that. The general operating principle of each pedal type is also introduced.

Regardless of pedal type, also other functions are controlled with the foot controller. Somewhat common solution is to have a separate joystick or joypad -type controller on the foot controller with the sole purpose of controlling the chair. Most of the observed foot controllers have 2-4 additional buttons or sliding switches to control various functions of the dental care unit. As the operating logic of the various foot controllers are unknown, this categorization will not take them in to account and makes the classification solely based on the type of power control.

Figure 3: Universal-pedal controller (air valve / button)

The universal-pedal (Figure 3) activates power on instrument when pressed at any position. Typical design based on pneumatics implies that no power control is available and the pedal has rather just an on-off functionality for instrument control.

Figure 4: Combined sliding-pedal

Combined sliding-pedal (Figure 4) has a lever that is used for power adjustment. Power is activated at set power level when pressing down the lever. Set power level is kept until the pedal is slid to a new position.

Figure 5: Pedal controller (gas pedal / sewing machine pedal)

Pedal controller (Figure 5) activates power when pressed. The further down the pedal is pressed, more power is applied on instrument. Once released, the pedal returns to neutral position. Working principle is analogous to a sewing machine or car throttle pedal.

Figure 6: Sliding-wheel controller (spring return, neutral center)

Sliding-wheel controller (Figure 6) activates power when the lever is pushed to either side from the neutral position. The further the lever is moved from the neutral position; more power is applied on instrument. The pedal returns to neutral position upon being released.

Figure 7: Spring-return controller (spring return, neutral left or right)

Spring-return controller (Figure 7) activates power when the lever is moved from neutral position. The lever returns to neutral position upon being released. The further the lever is moved from the neutral position; more power is applied on instrument.

Regardless of the implications that a certain foot controller type would be superior to others regarding ergonomics of operation (Gerhard 2011), user preference on the power control method needs to be addressed when offering equipment. In addition, the working habits and positions of dentists vary heavily, which means that it is likely that there is not a single solution that offers optimal performance for all users. It was observed that several dental equipment manufacturers have identified this and offer two or three different foot controllers with alternative power control method.

3 Design of foot control case study

In this chapter, the case study of this thesis is presented. The background, research question, research methods and material is introduced.

3.1 Background

The background of the case study is that a new dental care unit has been under development and a new foot controller is needed to accompany it. In addition, all the requirements imposed by the standards and ergonomic requirements are to be considered during the design process. The case study will be a part of the design process and serve as the ground work for the foot controller design.

3.2 Research question

The research problem of this thesis is, how very low fidelity prototypes could be used as effectively as higher fidelity prototypes in gathering user feedback and identifying the most desirable combination of feature parameters?

To find an answer to the research problem, the answer is sought for the following research questions:

1. Could ultra-low fidelity prototypes be used to find out usability related design parameters as effectively as higher fidelity prototypes?
2. How prototype fidelity effects on the usability experience of the prototype?
3. How prototypes can help to discover user needs?

3.3 Research methods and material

This chapter discusses the research methods used in this thesis and how material was gathered.

3.3.1 Research methods

The research combines qualitative and quantitative methods and presents the gathered information to give a more extensive view on the subject at hand. The research was done in steps in which information from previous step was used in the next step and the phases of the research can be seen in Figure 8. This type of research is known as mixed-methods research.

Creswell (Creswell 2014) describes the multiple phase mixed-methods research to contain several independent experiments or steps which all share a common focus. Each phase of the information gathering is like a small research as themselves and they are analyzed before the next phase. The previous phase gives information which is then used in the next phase.

As the subject for the research was not familiar before, the research began by surveying dentists, the main users of dental care units, to gather information on what do they want from their equipment and what are the undesirable features. Also, information about how they use the foot controller was gathered. The results of the first phase were analyzed and the design and building of prototypes was based on the information gathered from the dentists. Interviews were then conducted with the prototypes as the center of the conversation, so users would test and evaluate them and give feedback on usability aspects.

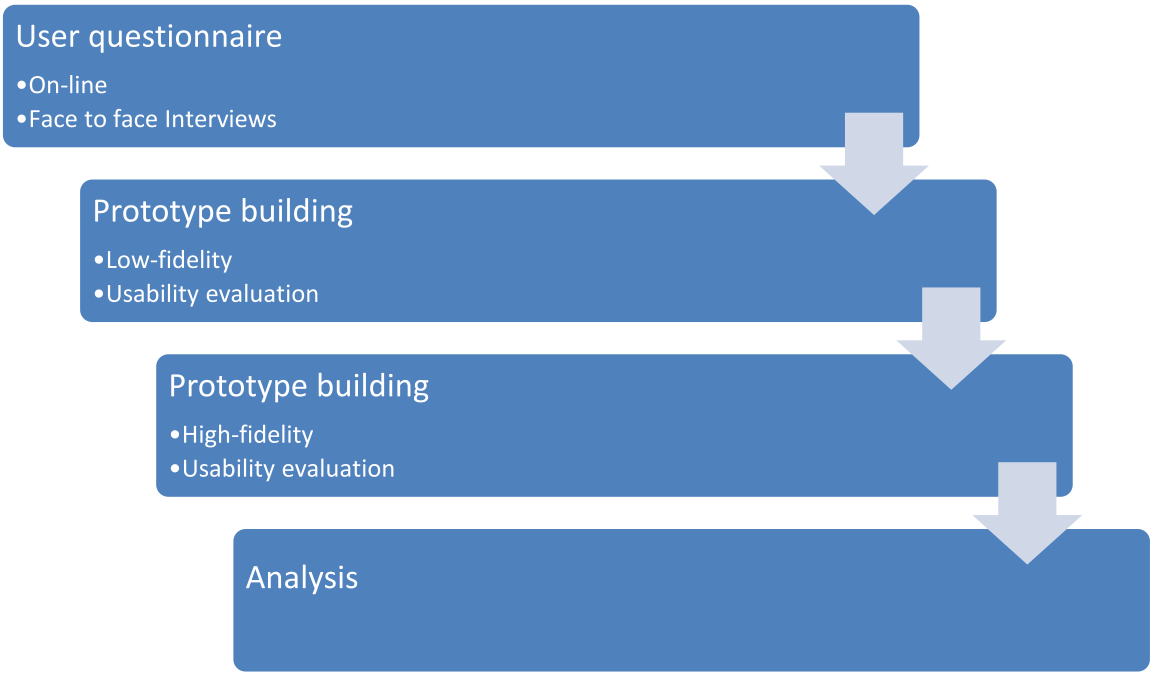


Figure 8: Research phases

The user questionnaire was designed to gather both quantitative and qualitative data. Analysis of open fields in questionnaire was done mainly with affinity chart. Quantitative data provided mostly background information and qualitative data was the focus in the questionnaire. Analysis of the interviews of dentists was done with content analysis and the evaluation of prototypes was done with orthogonal arrays to find the optimal parameter combination.

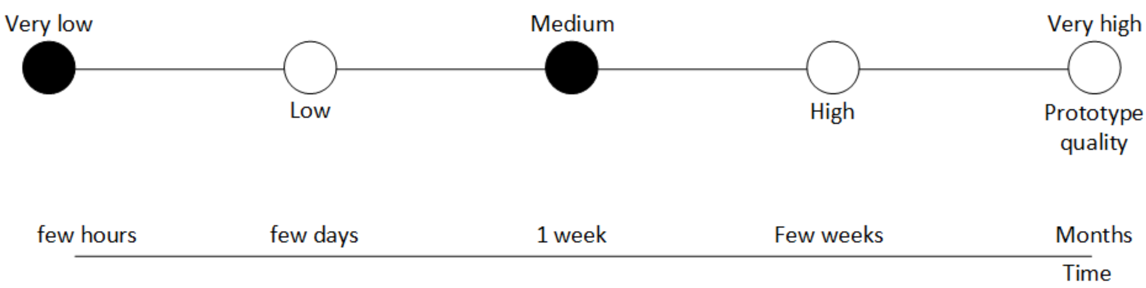


Figure 9: Prototype fidelity timeline

As mentioned earlier, there are multiple ways to define prototype fidelity. The various classifications of prototype fidelity introduced in chapter 2 are multi-dimensional and sometimes even somewhat complex. To define fidelity, one needs to know various bits of background information, design criteria etc. In this thesis, the definition of prototype fidelity is taken to the simplest possible level and definition is done based on the one thing that is in most cases the limiting factor and most difficult to manage as a resource, time. To define the fidelity of the prototypes in development, a novel metric is introduced here. The prototype fidelity can be expressed as a timeline as seen in Figure 9. There are several factors that have an effect to the result of the design and making of a prototype. Those are the experience and skills of the maker, known requirements for the prototype and time and build materials available for designing and making the prototype. If the experience and skills of the prototype maker are low, a very high-quality prototype may not be possible to achieve. Regardless of skills and experience, a very low fidelity prototype can always be made. This means that the skills and experience of the prototype maker can be argued to have only effect on the highest achievable fidelity level, when making prototypes. Known requirements for the prototype influence on how well will the result respond to the needs of the user. This means that a prototype can be made even with rather low amounts of background information. On the other hand, available resources cannot be claimed to have a big influence on the fidelity level of the prototype, because very high-quality prototypes can be built with for example scrap material. What can be agreed on is that the limiting factor regarding prototype fidelity is time available. The less time at hand, the lower quality or less features can be achieved in the making of the prototype. With increasing time at hand, resources and skill, the prototype can be designed and made to resemble more an end product. Considering the dimensions of role, implementation and the look and feel, the prototype shifts from sampling one or two of the dimensions towards taking all dimensions in to account and integrating the user experience as a whole (Houde, Hill 1997). This essentially means that with enough time passing, the prototype should represent the final product.

3.3.2 User questionnaire

This chapter discusses the online questionnaire, which was done to get customer insight. The quest for finding user needs began with an online questionnaire. The aim was to gather a baseline, which could be used to specify more detailed requirements of a foot controller.

To see, how the replies represent dentists as a professional group, the questionnaire had several background information questions height, gender and working experience of the dentist. Rest of the questionnaire focused on exploring user experience about dental care unit foot controllers and on operating the dental care unit with the foot controller. Likes and dislikes were gathered of the current and previous foot controllers the dentists have operated. The questionnaire was done in Finnish as it was sent only to Finnish dentists.

The questionnaire was used to map features of the foot controller, which dentists consider to be most important and most problematic. Respondents were asked to list three most important features and three most problematic features of a foot controller. Questions were open so to ensure that no anchoring to options on a given list would happen and all possible features could be listed as respondents saw them. The respondents were also asked, which type of power control method they would prefer out of three options: gas pedal, spring return and a combined sliding pedal. There was no compensation offered for the completion of the questionnaire, to ensure that participants filling out the questionnaire were motivated by the right reasons, such as the wish to participate in the development of a foot controller for a dental care unit, and not by the possible compensation.

Oral interviews also supplemented the questionnaire to ensure that critical information was not lost while gathering information via survey. The interviews were structured similarly as the questionnaire and same questions were asked. The interviews were done in English or Finnish depending on whether the interviewee was Finnish speaker or not.

The questions of the questionnaire were the following:

Dental unit foot control questionnaire (Appendix 1)
Questions 1, 2, 5 and 6 were demographics.
3. In my opinion, the three most important features of the foot controller are:
4. In my opinion, the three biggest problems of the foot controller are:
7. The power control method I prefer is
8. List the features you want to control with the foot controller
9. When I operate the dental care unit I have to move the foot controller
10. When I operate the dental care unit I have to look at the foot controller
11. The foot controller must be
12. Free comment

3.3.3 Prototype interviews

This chapter discusses the prototype evaluation and interviews of the dentists.

To get a more thorough understanding about the needs of the dentists and how the foot controller should work, prototypes were built and dentists were asked to evaluate them and analyze how they would fit their needs. Also by showing the prototypes to potential customers, it could be found out, how well the proposed designs would meet the requirements set by standards, ergonomic requirements, and principles of universal design.

The volunteers for testing of the prototypes were gathered through two channels. The user questionnaire had an opt-in clause for the next phase of the study. By leaving contact information, the respondent expressed their wish to continue in participating in the next steps of the development process. Also, a separate invitation to participate in the testing was sent through one of the dental societies active in Finland.

Dentists tested the prototypes and gave feedback about their performance and features. The testing was planned to happen at the clinic where the dentist works at. This way a more authentic environment was present and the dentist testing the foot controller could do the testing with their own work setup such as personal working stool or working shoes. Also, clinic environment provides context when evaluating the prototype as an extension of the working environment and not just as standalone product. This engages the first dynamic of learning (Hyysalo 2006).

To minimize the number of prototypes to be made, parametric prototypes were built, which could be varied in terms of the most important properties identified in the questionnaire. The dentists were presented prototypes of two different fidelity levels and four different parameter combinations, eight different models in total.

Table 14: Array for foot controller variables

Variable	*Relevance to usability*	*levels*
Size	Movement range, maneuverability	small / large
Number of buttons	No. of controllable functions with single actuating action	2 / 4
Location of buttons	Working ergonomics, operating logic	top / side

The variable parameters are presented in Table 14. These parameters were determined to be most critical regarding the usability and functionality of the foot controller. The size of the base was selected as it effects the required movement range of dentists' foot to operate the foot controller.

Number of buttons relates to the number of features of the dental care unit which are controllable with the foot controller. The greater number of buttons may also contribute to the experienced complexity of the use of the foot controller.

Location of the buttons relate to the working ergonomics of the foot controller. Top positioning encourages to operate buttons by pressing them and side orientation more often a sliding motion of the foot.

The testing order was randomized to mitigate any possible errors resulting from systematic testing order. Because people work at a different pace, the testing time was not limited in advance to a specific amount of time per prototype but rather testing was continued the duration the dentist was giving feedback on any specific prototype variant.

Each of the prototypes were evaluated with a short evaluation form (Figure 10) with 9 usability related features to evaluate. The evaluation scale was from 1-5 with low end representing poor and high end excellent.

Konfiguraatio				

Arvioi asteikolla 1-5 seuraavia väittämiä							
		1	2	3	4	5	
Käytön helppous	Heikko						Erinomainen
Nostaminen	Heikko						Erinomainen
Työntäminen jalalla	Heikko						Erinomainen
paikallaan pysyminen	Heikko						Erinomainen
herkkyys	Heikko						Erinomainen
vivun liikematka	Heikko						Erinomainen
vivun tuntuma	Heikko						Erinomainen
Käytettävyys	Heikko						Erinomainen
Jos saisin itse valita, ottaisin tämän polkimen	Ei koskaan						Ehdottomasti

Vapaa kommentti:

Figure 10: Evaluation form for prototype evaluation

The evaluation forms were collected together and analysis was performed with classical Taguchi array analysis. The mean plot shows, which parameters are most preferred among the dentists and the SN -ratio can be interpreted how much did the respondents agree on a specific statement.

4 Results

This section discusses the results of the case study.

The research questions were as follows:

1. Could ultra-low fidelity prototypes be used to find out usability related design parameters as effectively as higher fidelity prototypes?
2. How prototype fidelity effects on the usability experience of the prototype?
3. How prototypes can help to discover user needs?

As further analysis in section 4.2 shows, based on the case study, the answer to the main question is that, there is no noticeable difference in the identification of usability related parameters when comparing high and low fidelity prototypes. The differences that were observed between low and high-fidelity were mainly related to the visual refinement and feeling of the prototypes. As the prototypes tested mainly the implementation dimension and not the look and feel (Houde, Hill 1997) the further analysis of these observations is beyond the scope of this thesis and thus will not be thoroughly analyzed.

The answer to the first sub question is that prototype fidelity effects on usability experience through the look and feel of the prototype. As the higher fidelity prototype is closer to a final product, it has a more sophisticated feeling in moving parts and it is visually more appealing. On the other hand, low fidelity prototypes can achieve similar functionality as higher fidelity prototypes.

The answer to the second sub question provides more insight to the relationship between users and the identification of their needs. What was found out during the case study was that more needs and issues with existing designs could be identified when a prototype was present in the interview. When the dentist could fiddle with something physical, they could remember more easily issues they have had with their current or previous equipment. It appeared to be easier to give more accurate details about the needs for a foot controller when the prototype was present.

4.1 User questionnaire

The on-line questionnaire was sent out to roughly 300 dentists working in Finland. Contact information was gathered from etsihammaslääkäri.fi portal, which is a database for contact information of over 1000 dentists operating in Finland. The questionnaire got 64 responses.

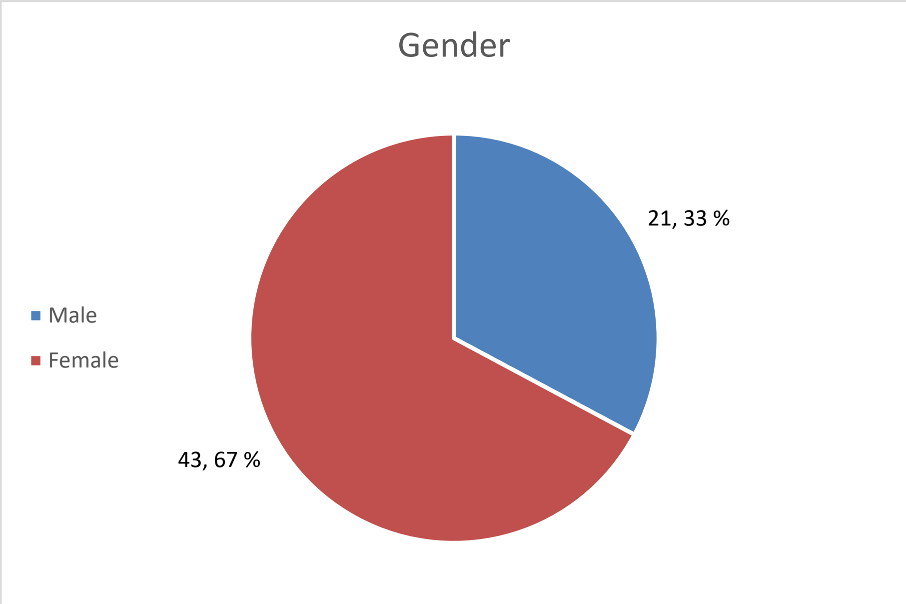


Figure 11: The division of respondents based on gender

As seen on Figure 11, roughly 2/3 of the respondents were women and 1/3 were male. As Figure 12 shows, about 60% of the respondents had working experience of over 20 years. 15% had 0-5 years and 15% had 6-10 years of working experience.

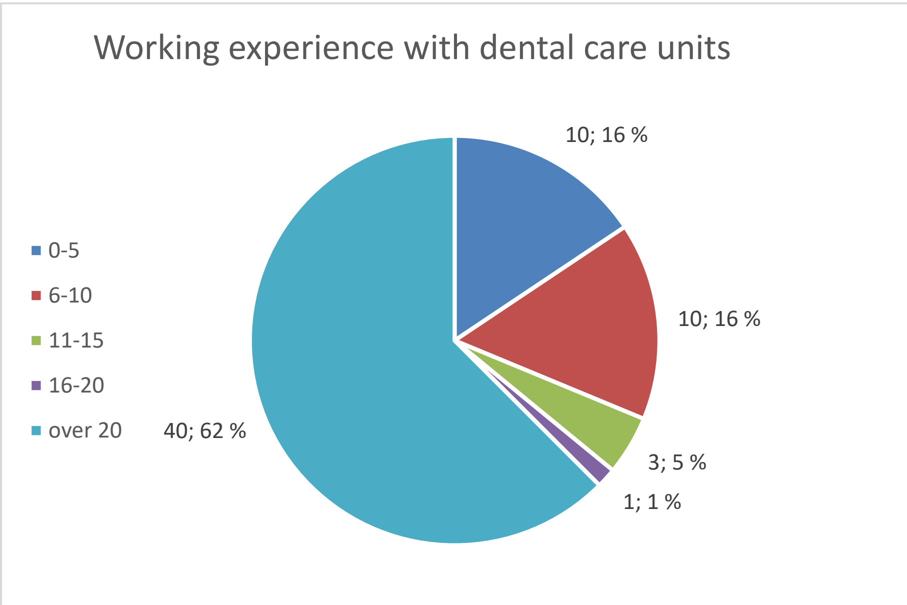


Figure 12: Division of respondents based on working experience

The open field answers were sorted with affinity diagram -method to identify the needs of the dentists. The resulting groups describe a common feature of the foot controller. The priority of the most important and problematic features is established based on the number of times a feature is mentioned in all of the forms.

Three most important features of the foot controller are:

- Stability (it stays in place while in use)
- Easy to use (simple and light to operate actuators)

- Robust (error free operation)

Three most problematic features of the foot controller are:
- Stability (it moves around while in use)
- Difficult leg movement (too long and awkward leg movement required)
- Inaccurate power control (the power control actuator does not feel good to use)

The most preferred power control method was the spring return (70.3%) and the gas pedal was basically the other option (26.6%) as the combined sliding pedal got only 2 votes (3.1%)

What was found out was that the questionnaire did not give an explanation about why dentist must move the foot controller or why do they need to look at it while operating the unit. Seven oral interviews were conducted and they filled out some of the blanks left unanswered by the on-line questionnaire. Depending on the working habits of the dentist, the need for moving of the foot controller comes from the changing of the working position or from poor grip of the foot controller on the floor. Most of the time, the need to move the foot controller comes from changing the working position.

The interviews revealed that the need to look at the foot controller results from three different reasons. Firstly, the dental care unit is new to the dentist and operating logic differs from the previous units the dentist has been operating, and the "break in" time is still ongoing and the operator is familiarizing to a new unit. Second, the foot controller moves during use and the pedal is "lost from the foot". Third, the pedal has too many features or the feel of the actuators is so poor that the operator needs to look at which actuator is being activated. The first reason is acceptable because getting accustomed to new equipment will always take some time. The second reason is an issue that needs addressing as a moving foot controller slows down the work of the dentist. Moving occurs because of two reasons; the friction between the foot controller and the floor material is not adequate or the dentist operates the foot controller in a rough manner and in moves as a result. The third reason for needing to look at the foot controller is illogical layout or poor design of foot controller actuators, which is unacceptable and rather is a sign of a failed design.

4.2 Prototype interviews

Figure 13: Prototypes ready for testing

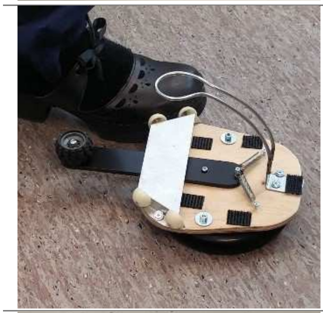
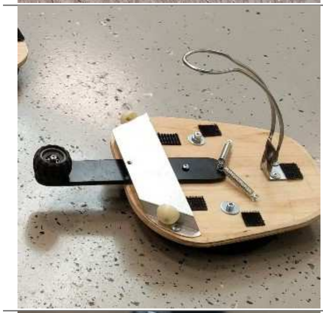
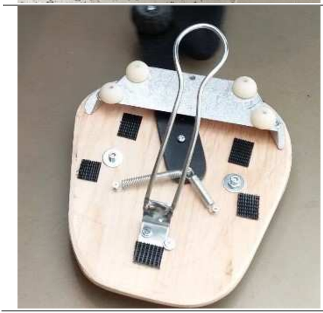
The fidelity levels for the foot controller prototypes which were built, were chosen as very low and medium. As the time to complete a prototype significantly increases as the target fidelity of the prototype increases, very low fidelity was selected for the first prototypes. The higher fidelity was set to medium, so the design and build time would stay reasonable. In this case the time to design and build the two very low fidelity prototypes was around 8 hours in total. The medium level prototypes were complete in 5 working days. The low fidelity prototypes were built from scrap material laying around and simple hand tools were needed in the making process. Medium level prototypes took longer to design than very low fidelity prototypes, when comparing design time to total build time. More sophisticated manufacturing was also used as the base was laser cut, levers were milled with a CNC-router and the shells were 3D-printed. Also, ready components were used to give the medium fidelity prototypes a more finished look.

The questionnaire got 9 opt-in responses and the separate invitation, which was sent to about 1000 dentists as a part of the weekly newsletter of the dental society got 20 responses. A total of 18 dentists tested and gave feedback on the prototypes. The testing of the prototypes was mostly done at the clinics where the interviewed dentists worked at. Six interviews were conducted outside of clinic environment. The tested prototype versions can be seen in Table 15.

Most of the dentists testing the prototypes work in sitting position and have shoes on. Some were standing and others did not use shoes with the foot controller. This information seems to be relevant to the feedback of different variations of the prototypes. Depending on the working position of the dentist, the preference for foot controller button position varied. Based on the interview results, a more in-depth study is needed to validate this find.

5 dentists did not test all the prototypes. 3 dentists left blank answer for an evaluation criterion for one or more evaluated prototypes. A total of 10 dentists tested all of the prototypes, their variants and answered the evaluation forms without leaving blanks.

Table 15: Parametric prototype configurations

Fidelity Low	Base	No. of buttons	Location of buttons	Fidelity High
	Small	2	Top	
	Small	4	Side	
	Large	2	Side	
	Large	4	Top	

The prototypes were presented for evaluation in a random order, depending on the amount of feedback a dentist wanted to give on a variant, the testing lasted 30-90 minutes in total. Typically, most feedback was given for first two or three prototypes tested and the amount of feedback gradually decreased as more prototypes were tested. Also, what could be seen was that after first two or three prototypes tested, the dentists started to compare the prototype in testing to the previous tested versions and comments changed from commenting on a particular feature of the prototype to stating if the current prototype was better or worse in some aspect than the previous ones tested.

During the prototype interviews it became clear, dentists work in various ways and if one operates the foot controller standing and without shoes, the other may be sitting down with wooden clogs on. Based on the interviews, dentists are a quite heterogenous group and standardized testing setup may not fit all users. The prototypes were tested in both sitting and standing position and with or without a shoe depending on how the dentist had familiarized oneself to operate a foot controller.

The evaluations were analyzed with the classical Taguchi array tool of JMP statistics. Each evaluation was input as a separate run and the analysis was done to high and low fidelity prototypes separately. The results of each analysis were gathered to a table to see which variant was most preferred when comparing to the evaluation criteria. The most preferred variant for each evaluation criteria and prototype fidelity level is listed in Table 16. The table is compiled based on the highest mean values of each prototype parameter. It needs to be pointed out that in many cases, the differences in some cases regarding feature mean is 0,1 or less, so this table does not necessarily provide the absolute truth about best parameter combination. Rather it should be viewed as a reference to which parameter combination could provide the best user experience considering all of the parameters. Further information on the results of the testing are shown in appendix II.

Table 16: Prototype testing results

Evaluation criterion		*Lo-Fi*	*Mean*	*S/N ratio*	*Hi-Fi*	*Mean*	*S/N ratio*
Sensitivity	Base	small	3,96	9,61	small	4,11	11,61
	Buttons	2	3,95	8,68	2	4,07	11,23
	Location	Top	3,91	9,42	Side	4,11	11,63
Usability	Base	Big	3,07	6,95	small	3,54	8,94
	Buttons	2	3,20	6,84	2	3,38	9,23
	Location	Top	3,06	5,98	Top	3,49	9,53
Ease of use	Base	Big	3,33	7,30	small	4,01	11,35
	Buttons	2	3,46	7,70	2	3,87	11,06
	Location	Top	3,37	6,91	Top	3,83	10,76
Lifting	Base	small	2,78	4,59	Big	3,68	8,23
	Buttons	4	2,75	4,07	2	3,70	8,21
	Location	Side	2,76	4,89	Side	3,79	9,09
I would take this	Base	small	2,51	4,75	small	3,08	5,99
	Buttons	2	2,45	4,59	2	2,97	5,52
	Location	Top	2,45	4,56	Top	2,97	5,25
Staying in place	Base	Big	4,23	11,55	small	4,16	11,80
	Buttons	4	4,21	11,70	2	4,41	12,57
	Location	Side	4,36	12,04	Side	4,18	11,85

The table is read in blocks which consist of the evaluation criterion, for both fidelity levels: preferred base size, number of buttons, location of the buttons, and the mean and S/N ratio for each parameter. The prototypes were evaluated as complete entities but because of the selected analysis method, the grade for each design parameter can be examined separately. The most preferred parameter value for each evaluation criteria for both prototype fidelity levels are listed, following them are the mean and S/N ratio for the parameter. If the S/N ratio is high, over 10, it means that the dentists have agreed with each other when evaluating the prototypes and have given similar grades to the prototype. If the S/N ratio is low, five or less, it means that the testers have disagreed among each other when evaluating the prototypes and their responses are more spread out along the evaluation scale.

What was interesting to find out is that regardless of the fidelity level, the most preferred variant was a foot controller with two buttons on top. In general, two buttons on top was most preferred combination of controls. With low fidelity prototypes, the bigger body was most preferred and small body with high fidelity prototypes.

Based on the questionnaire and interviews done before the prototype interviews, the compact size and simple operating logic of two buttons on top was somewhat anticipated to be most preferred variant. What was insightful about the interviews was that the fixation for a certain style of foot controller can start as early as in school for dentists. The first equipment they use at dentistry studies may have an effect on what kind of a foot controller the dentists prefer on their equipment, as some dentists testing began to reminisce all of the different foot controllers they had used during their career. As stated earlier, one of the most desirable properties of a foot controller is simplicity and clarity in use. This desire shows in the testing of the prototypes, not only in the results but also in the comments and discussions that were had during the testing sessions.

Some of the differences in the results may be explained by the difference in the way the prototypes were built. The low fidelity prototypes were too light at first so a weight was added to the base of the base of both. This resulted in the height to increase by the thickness of the added weight, approximately 30mm, and for most testers resulted in discomfort in testing. The higher fidelity prototypes had the handle as a mirrored part, so two variants had an open-ended handle pointing left and two pointing right. In practice, these worked differently depending on, which foot was used for lifting. Also, the side levers worked differently whether narrow or wide body was used, because the rotating joint of the lever was set at a fixed distance. Not all of these differences effect on the same evaluation criteria but it is plausible that these differences caused shortcomings to some variants and the dentists would evaluate them differently than they would have otherwise.

Here the analyses of foot controller usability and sensitivity are presented and discussed. The results of the low-fidelity prototypes are compared to high-fidelity prototypes. The results of the analysis are presented in a cube plot form as it is an effective way to present information regarding three bi-level parameters. Each of the corners represent one of eight possible parameter combinations and upper number is the mean grade the combination gets and the lower is the S/N ratio. The results of the analysis will not be scrutinized heavily at this point, as the Taguchi method is a two-step process and the made experiment needs a verification needs to be ran. The full details of the analysis of the usability parameters can be found in Appendix II in the form of JMP output.

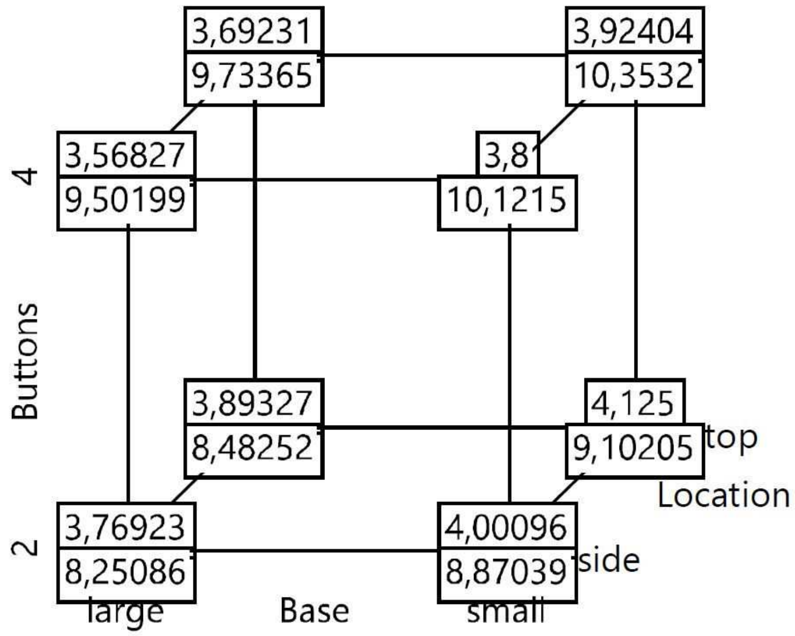


Figure 14: Lo-fidelity sensitivity

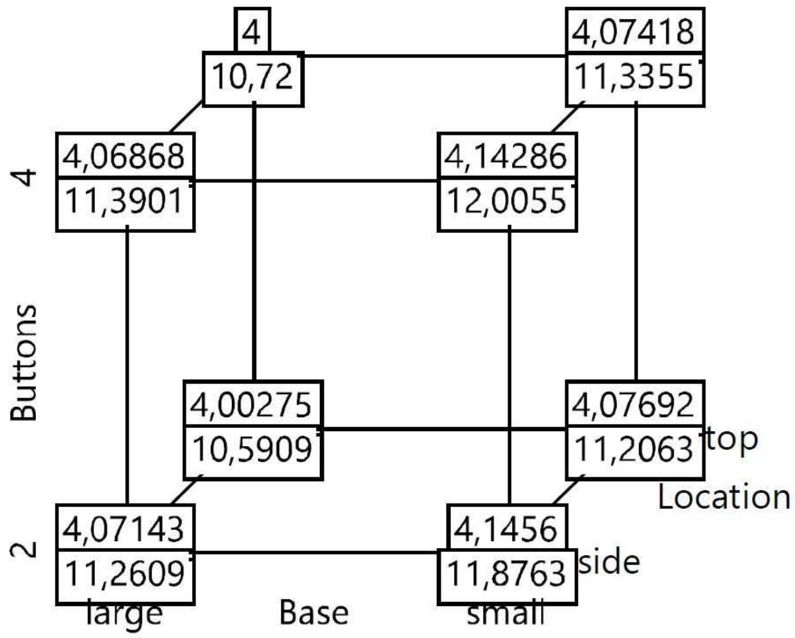


Figure 15: Hi-fidelity sensitivity

As usability parameter, sensitivity answers the question how sensitive is the controller to operate. The results of the analysis can be seen in Figure 14 and Figure 15. The most sensitive parameter combination with low-fidelity prototypes was a variant with a small base and 2 buttons on top. The most sensitive parameter combination with high-fidelity prototypes was a variant with a small base and 2 buttons on side. Preferred variant with both fidelity level prototypes were strongly agreed upon. During the interviews, the dentists focused mainly on the feeling of the power control lever as it was the only moving component on all the prototypes. During the discussion however, the answers of the dentists indicate that some also considered the sensitivity of the side mounted levers on the high-fidelity prototypes, as they were also moving. The smaller sized body was preferred on both fidelity levels regarding sensitivity. This was apparent also in the discussions with the dentists during testing as many commented on the small required leg movement to operate the foot controller. Number of buttons was preferred to be two on both but higher fidelity prototypes almost the same evaluation regardless of number of buttons. Location of the buttons was preferred to be on top with the low fidelity prototypes but side with the high fidelity. This indicates that the dentists experienced better sensitivity in operating the side mounted levers rather than buttons.

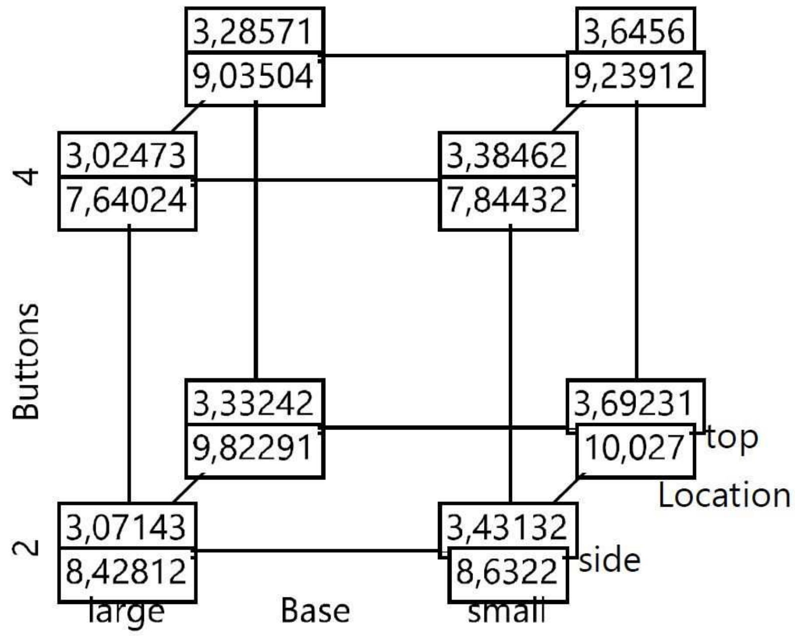


Figure 16: Hi-fidelity usability

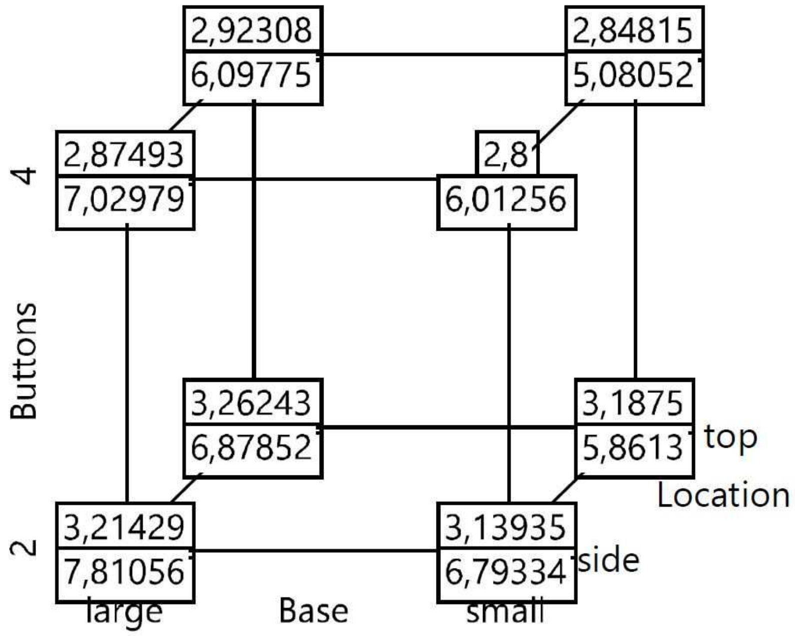


Figure 17: Lo-fidelity usability

Usability was overall rated similarly regardless of prototype fidelity. The results of the analysis can be seen in Figure 16 and Figure 17. The most usable parameter combination with low-fidelity prototypes was a variant with a large base and 2 buttons on side. The most usable parameter combination with high-fidelity prototypes was a variant with a small base and 2 buttons on side. Preferred variant with both fidelity level prototypes were strongly agreed upon. Both received grades which averaged close to the middle of the scale but feature wise preferences differed. With low fidelity prototypes, big base and buttons on top were more preferred, but only marginally. On the other hand, two buttons were strongly preferred over four buttons. On high-fidelity prototypes, small base and buttons on top were evaluated to be better. Number of buttons appeared to be indifferent regarding usability.

When evaluating the ease of use, on low-fidelity prototypes the size of the base had no impact on the experience on the ease of use. Two buttons were preferred and button location on top. High fidelity prototypes had stronger reaction to the small base, which was preferred. Two buttons on top was also the preferred combination.

Regarding lifting, the small base was preferred on the low fidelity prototypes and button location on the side. On high-fidelity prototypes, big base was slightly more preferred and strong preference on mounting buttons to the side.

Any of the prototypes were not highly appealing to the dentists as the average was left below the middle option. Both fidelity prototypes indicate preference of small base, two buttons on top.

Staying in place was evaluated good on both fidelity prototypes. Side mounted levers on high fidelity prototypes resulted in some movement out of place when the foot was slid over them.

5 Discussion

In this section, the results of the case study are viewed from broader perspective and connected to the big issues described in the introduction.

The thesis objective was to explore the effects of prototype fidelity on usability evaluation and how prototype fidelity effects on the feedback given by the user. A case study on the design of a foot controller for a dental care unit was conducted to fulfill the objective. As the research results discussed in chapter four indicate, the prototype fidelity has little to no effect on the usability evaluation. The results are encouraging as low-fidelity prototypes are in general cheaper and faster to design and manufacture, so feedback from users can be gathered at an earlier stage of the design process. Also, more feedback can be gathered as there is the possibility to make more design iterations.

The case study also provides insight to the development process of a dental care unit foot controller. The information gathered is such that it can be used to justify design choices and advance the design process to the next stage. User involvement is mandatory in MDD&A process and the earlier user involvement is in the development process, the more certain it will be that the end-product will full fill the expectations of all stakeholders.

During the testing of the low and higher fidelity prototypes, it was revealed that the differences in the two different fidelity level prototypes were such, that it can be argued, whether the differences caused distortion in the responses. Though, based on the interviews and the evaluation form, it is not possible to analyze how the differences effected the performance of a specific prototype variant in the testing. At least the following differences were identified from the comments of the testers:

- Low fidelity prototypes may have suffered in usability evaluation because of the weight attached to them that caused the height of the prototypes to change.
- High fidelity prototypes had open-ended handles that performed differently than the closed loop handles on the low fidelity prototypes.
- The length of the levers and tips of the levers differed significantly between the high and low fidelity prototypes.

Another thing to contemplate on is, whether the chosen fidelity levels for the prototypes were right or should the low fidelity prototype have been a higher level and the higher fidelity prototype even higher. The low fidelity prototypes received a few times quite surprised comments on their esthetics. If the interviewee comments that the prototype is an interesting looking rat trap, how can the designer be certain that the feedback given is true and appropriate? In general, though the interviewees were briefed about the rough look of the prototypes and during the testing of them it became apparent that the dentists could actually see beyond the external appearance and analyze the prototypes in an appropriate manner.

Because the case study was done parallel with the development of actual product, ideas deemed worth testing were implemented to the prototypes as they came up. The low fidelity prototypes were made first and a few interviews were made with using only them. Based on the feedback and internal discussion, a few ideas were implemented to the high-fidelity prototypes. For example, the high-fidelity prototypes had added features that low fidelity prototypes were lacking. The power control lever was modified and a push down functionality was added. The side mounted button functionality was implemented as a lever instead of a button. Based on the comments from dentists during testing, these modifications had an effect on the testing results but the extent cannot be evaluated as no metrics were used to monitor them. The high-fidelity prototype got both positive and negative comments about the levers that replaced the buttons for side mounted button variants.

One of the shortcomings in the case study is noise factors were not defined and a second, confirmatory run was not conducted. Due to the intensiveness of the testing and number of voluntary testers, it was decided to be left out from this thesis. A confirmatory run with noise factors is necessary to verify the results. This will be conducted with the next iteration of the foot controller prototype.

What was also found out during interviews is that dentists have strong preferences regarding their equipment they use and this effects on the way they evaluate the prototypes. Some have developed strong preference to a certain feature by getting familiar to a single manufacturer equipment over a long period of time. Others have operated various units from different manufacturers and have developed their preference based on what suits them best, although seldom do the dentists working with various units at different locations get to have a say on which unit they operate. Due to the nature of how medical devices are regulated, it is likely impossible to fulfill the request from some of the dentists that they could use the same foot controller on different manufacturers' equipment.

5.1 The utilization and generalization of the results

The general assumption that a prototype must be high-fidelity and polished model of a product to provide useful insights, is outdated. The results confirm, what previous research has also stated, that prototype fidelity is not a problem, which needs much attention. In this case, if operating logic and functions of a product in development are the features that are wanted to be tested. Prototypes give context to intended users of the product in development and thus it is beneficial to have some kind of prototype, be it an extremely low fidelity prototype or a high-fidelity prototype. This information can be utilized in any product development project and could be summarized by phrase: "what you can touch and feel, you can tell how you feel about it."

The literature review part of this thesis can be used in various product development projects focusing in user centric and user-friendly design. Chapter 2.3 is applicable only in development of a medical device and chapter 2.5 and 3 are applicable only to the development of a foot controller for a dental care unit.

The case study serves directly as ground work and basis for the development of a foot controller for any dental care unit, as long as it is acceptable that the majority of the feedback has been gathered from Finnish dentists working mainly in the capital area of Finland.

5.2 New information provided by this thesis

The novelty of this thesis comes from the way it deals with prototype fidelity and testing of the prototypes. The simplified definition of prototype fidelity is not an attempt to be a substitute to more sophisticated definitions and frameworks for prototype fidelity such as the four dimensions of prototype fidelity (Virzi, Sokolov et al. 1996) or PFX (Menold, Jablokow et al. 2017). Rather it can be viewed as a supplement, which would help with the identification of fidelity of prototypes to be made or which are in the making.

It is difficult to find information that is about using robust design methods in evaluating design parameters based on user feedback and this thesis shows that it is possible to get results also in this application. Provided that the ground work is properly done, it is a feasible way to analyze the prototype.

5.3 Future development and research ideas

During the making of this thesis, several ideas for future development and research has come up. The focus for future research in the evaluation and testing of the introduced definition for prototype fidelity. It is likely that a one-dimensional framework to define prototype fidelity may be insufficient and it would be beneficial to further develop the introduced definition of prototype fidelity. One idea that came up is that the framework could be combined with an existing definition of prototype fidelity.

The research question, how prototypes can help to discover user needs, is one that would be interesting to get a more thorough answer. It could be worthwhile to find out if there is a threshold at which prototype fidelity inhibits the identification of needs and how much the presence of a prototype improves the user's ability to express their needs.

For future research, another idea is to further study how well the robust design methods work in product development when parameters and evaluation is based on opinions and thoughts of product users and not absolute measured values of performance.

The case study is the basis of future development of a foot controller for a dental care unit but it may serve as basis for development of other dentistry related equipment as well.

6 Conclusions

This thesis focused on early stages of product development process and how prototype fidelity effects on usability evaluation. The literature review and the case study together provides an oversight to the complex task to combine user needs and design guidelines and standards in to a product that would meet all of the requirements these pose on it. The results provide basis for the R&D team to advance the design process to the next stage and be confident that the design choices are based on actual user preferences. The next iteration of the design should reflect the results of this thesis and meet user requirements. The next stage prototype should also be tested by dentists to verify the design choices and ensure that the design still meets customer requirements and expectations. This thesis brings together relevant information for a user-centric development process focusing on the development of a foot controller for a dental care unit. The development of a new product is a long journey and it is beneficial to ask for potential customer opinions thorough out the process and not just in the end.

Customers are the ones who keep businesses running by purchasing the products companies sell. Nowadays the options for any customer are more diverse than ever. Because of this it is vital for companies developing new products to take potential customers in to consideration right from the beginning of the development process. It is never a good idea to try to compete with price because it tends to be so that there will always be some instance who will sell cheaper. A preferred way to approach is to justify for the customer purchase of a product by the added value of the product fits the needs of the customer. Only way to achieve this is to have the potential users of the product participating in the design process right from the ideation phase.

7 References

BOOTHE, C., STRAWDERMAN, L. and HOSEA, E., 2013. The effects of prototype medium on usability testing. *Applied Ergonomics,* **44**(6), pp. 1033-1038.

BUCHENAU, M. and SURI, J.F., 2000. *Experience prototyping.* New York City, New York, USA: ACM.

CAMBURN, B., DUNLAP, B., GURJAR, T., HAMON, C., GREEN, M., JENSEN, D., CRAWFORD, R., OTTO, K. and WOOD, K., 2015. A Systematic Method for Design Prototyping. *Journal of Mechanical Design,* **137**(8), pp. 081102-081102-12.

CONNELL, B., JONES, M., MACE, R., MUELLER, J., MULLICK, A., OSTROFF, E., SANFORD, J., STEINFELD, E., STORY, M. and VANDERHEIDEN, G., 4/1/97, 1997-last update, The Principles of Universal Design [Homepage of NC State University, The Center for Universal Design], [Online]. Available: https://www.ncsu.edu/ncsu/design/cud/about_ud/udprinciplestext.htm [4/3, 2017].

CRESWELL, J.C., 2014. *Research Design: qualitative, quantitative, and mixed methods approaches.* 4 edn. London: Sage Publications.

DERBOVEN, J., ROECK, D.D., VERSTRAETE, M., GEERTS, D., SCHNEIDER-BARNES, J. and LUYTEN, K., 2010. *Comparing user interaction with low and high fidelity prototypes of tabletop surfaces.* Reykjavik, Iceland: ACM.

ELLEKJÆR, M.R. and BISGAARD, S., 1998. The use of experimental design in the development of new products. *International Journal of Quality Science,* **3**(3), pp. 254-274.

FOLLETTE STORY, M., 2007. Applying the Principles of Universal Design to Medical Devices. In: J.M. WINTERS and M. FOLLETTE STORY, eds, *Medical instrumentation Accessibility and usability considerations.* FL: CRC Press, pp. 83-91.

GERHARD, C., 2011. The dental foot controller– The devil is in the detail. *Alumni international magazine,* (03), pp. 58-63.

HEISKANEN, E., HYYSALO, S., KOTRO, T. and REPO, P., 2010. Constructing innovative users and user-inclusive innovation communities. *Technology Analysis & Strategic Management,* **22**(4), pp. 495-511.

HOKWERDA, O., WOUTERS, J., DE RUIJTER, R. and ZIJLSTRA-SHAW, S., 2006. *Ergonomic requirements for dental equipment. Guidelines and recommendations for designing, constructing and selecting dental equipment.* european society of dental ergonomics.

HOUDE, S. and HILL, C., 1997. What do prototypes prototype. *Handbook of Human-Computer Interaction,* **2**, pp. 367.

HYYSALO, S., 2006. The Role of Learning-by-Using in the Design of Health Care Technologies: A Case Study. *The Information Society,* **22**(2), pp. 89-99.

KAULIO, M.A., 1998. Customer, consumer and user involvement in product development: A framework and a review of selected methods. *Total Quality Management,* **9**(1), pp. 141-149.

MENOLD, J., JABLOKOW, K. and SIMPSON, T., 2017. Prototype for X (PFX): A holistic framework for structuring prototyping methods to support engineering design. *Design Studies,* **50**, pp. 70-112.

OTTO, K. and WOOD, K., 2001. *Product Design: Techniques in Reverse Engineering and New Product Development.* New Jersey: Prentice Hall.

SÄDE, S., NIEMINEN, M. and RIIHIAHO, S., 1998. Testing usability with 3D paper prototypes—Case Halton System. *Applied Ergonomics,* **29**(1), pp. 67-73.

SHIBA, S., GRAHAM, A. and WALDEN, D., 1993. *A new American TQM.* Portland, OR: Productivity Press.

SYED GHULAM, S.S. and ROBINSON, I., 2006. User involvement in healthcare technology development and assessment: Structured literature review. *International J Health Care QA,* **19**(6), pp. 500-515.

TAGUCHI, G., CHOWDHURY, S. and WU, Y., 2005. *Taguchi's Quality Engineering Handbook.* 1 edn. New Jersey: John Wiley & Sons, Inc.

TILLEY, A.R., 2002. *The measure of man and woman : human factors in design.* Revised edition edn. New York: Wiley.

ULLMAN, D.G., 2003. *The mechanical design process.* 4 edn. New York, NY: McGraw-Hill.

URLICH, K. and EPPINGER, S., 2012. *Product Design and Development.* 5 edn. McGraw-Hill.

VIRZI, R.A., SOKOLOV, J.L. and KARIS, D., 1996. Usability problem identification using both low- and high-fidelity prototypes, *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* 1996, ACM, pp. 236-243.

WALKER, M., TAKAYAMA, L. and LANDAY, J.A., 2002. High-Fidelity or Low-Fidelity, Paper or Computer? Choosing Attributes when Testing Web Prototypes. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting,* **46**(5), pp. 661-665.

WHEELWRIGHT, S.C. and CLARK, K.B., 1992. *Revolutionizing Product Development: Quantum Leaps in Speed, Efficiency, and Quality.* Free Press.

YANG, M.C., 2005. A study of prototypes, design activity, and design outcome. *Design Studies,* **26**(6), pp. 649-669.

Appendix

Appendix I. Kysely hammashoitokoneen ohjainpolkimesta. 2 Pages
Appendix II. Output of prototype testing analysis. 12 Pages

Kysely hammashoitokoneen ohjainpolkimesta

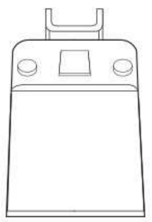
Tämän lyhyen kyselyn avulla kartoitetaan ohjainpolkimen toivottuja ja ei-toivottuja ominaisuuksia. Kysely on anonyymi

1. Olen
   - Mies
   - Nainen
2. Pituuteni on
   - alle 160 cm
   - 160-165 cm
   - 166-170 cm
   - 171-175 cm
   - 176-180 cm
   - 181-185 cm
   - 186-190 cm
   - yli 190 cm
3. Mielestäni ohjainpolkimen kolme tärkeintä ominaisuutta ovat:

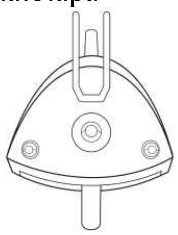
4. Mielestäni ohjainpolkimen kolme ongelmallisinta ominaisuutta:

5. Työkokemus hammaskoitokoneiden parissa vuosina:

   - 0-5
   - 6-10
   - 11-15
   - 16-20
   - yli 20 vuotta
6. Käytän poljinta yleensä _______ jalalla
   - vasemmalla
   - Oikealla
   - kummalla tahansa
   - Molemmilla
   - Muu
7. Mieluisin polkimen tehonsäätötapa



Kaasupoljin



Jousipalautteinen vipu

Liukuva vipu

8. Luettele toiminnot, joita haluat ohjata jalkapolkimella:

9. Kun käytän hammashoitokonetta, joudun siirtämään jalkapoljinta

1 2 3 4 5

En koskaan Aina

10. Kun käytän hammashoitokonetta, joudun katsomaan jalkapoljinta

1 2 3 4 5

en koskaan Aina

11. Jalkapolkimen tulee olla
    - Langallinen
    - Langaton
12. Vapaa kommentti

Least Squares Fit

Effect Summary

Source	LogWorth	PValue
Base	0,000	1,00000
Buttons	0,000	1,00000
Location	0,000	1,00000

Response Mean

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3,8466346	.	.	.
Base[large]	-0,115865	.	.	.
Buttons[2]	0,1004808	.	.	.
Location[side]	-0,062019	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,05369915	.	.
Buttons	1	1	0,04038554	.	.
Location	1	1	0,01538554	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	3,7307692	.	3,73077
small	3,9625000	.	3,96250

Buttons

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
2	3,9471154	.	3,94712
4	3,7461538	.	3,74615

Location

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	3,7846154	.	3,78462
top	3,9086538	.	3,90865

Response SN Ratio

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	9,3020206	.	.	.
Base[large]	-0,309764	.	.	.
Buttons[2]	-0,625566	.	.	.
Location[side]	-0,115833	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,3838157	.	.
Buttons	1	1	1,5653289	.	.
Location	1	1	0,0536691	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	8,9922563	.	8,99226
small	9,6117849	.	9,61178

Buttons

Least Squares Means Table

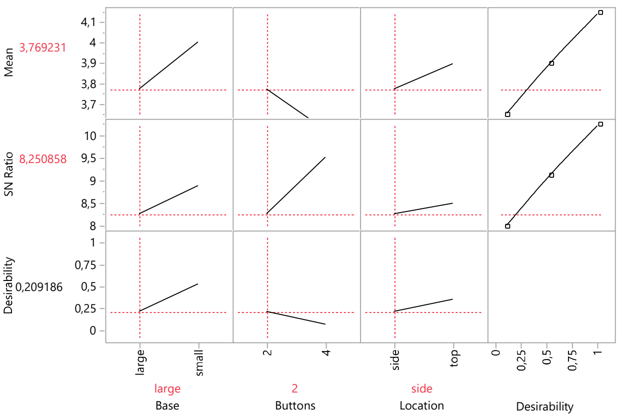
Level	Least Sq Mean	Std Error	Mean
2	8,6764551	.	8,67646
4	9,9275861	.	9,92759

Location

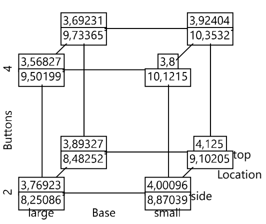
Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	9,1861876	.	9,18619
top	9,4178536	.	9,41785

Prediction Profiler



Cube Plot



HiFi_Sensitivity

Least Squares Fit

Effect Summary

Source	LogWorth	PValue
Base	0,000	1,00000
Buttons	0,000	1,00000
Location	0,000	1,00000

Response Mean

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	4,0728022	.	.	.
Base[large]	-0,037088	.	.	.
Buttons[2]	0,0013736	.	.	.
Location[side]	0,0343407	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,00550205	.	.
Buttons	1	1	0,00000755	.	.
Location	1	1	0,00471712	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	4,0357143	.	4,03571
small	4,1098901	.	4,10989

Buttons

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
2	4,0741758	.	4,07418
4	4,0714286	.	4,07143

Location

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	4,1071429	.	4,10714
top	4,0384615	.	4,03846

Response SN Ratio

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	11,298179	.	.	.
Base[large]	-0,30772	.	.	.
Buttons[2]	-0,064585	.	.	.
Location[side]	0,3350174	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,37876522	.	.
Buttons	1	1	0,01668477	.	.
Location	1	1	0,44894659	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	10,990459	.	10,9905
small	11,605898	.	11,6059

Buttons

Least Squares Means Table

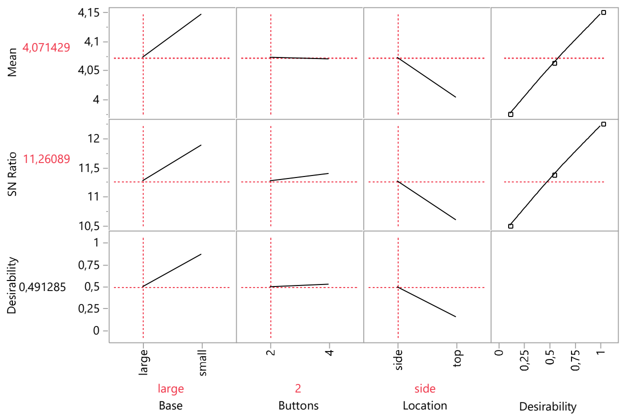
Level	Least Sq Mean	Std Error	Mean
2	11,233594	.	11,2336
4	11,362764	.	11,3628

Location

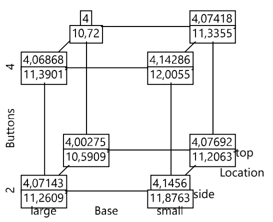
Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	11,633196	.	11,6332
top	10,963161	.	10,9632

Prediction Profiler



Cube Plot



Least Squares Fit

Effect Summary

Source	LogWorth	PValue
Base	0,000	1,00000
Buttons	0,000	1,00000
Location	0,000	1,00000

Response Mean

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3,0312157	.	.	.
Base[large]	0,0374657	.	.	.
Buttons[2]	0,1696772	.	.	.
Location[side]	-0,024073	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,00561470	.	.
Buttons	1	1	0,11516141	.	.
Location	1	1	0,00231800	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	3,0686813	.	3,06868
small	2,9937500	.	2,99375

Buttons

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
2	3,2008929	.	3,20089
4	2,8615385	.	2,86154

Location

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	3,0071429	.	3,00714
top	3,0552885	.	3,05529

Response SN Ratio

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	6,4455435	.	.	.
Base[large]	0,508611	.	.	.
Buttons[2]	0,3903878	.	.	.
Location[side]	0,4660201	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	1,0347405	.	.
Buttons	1	1	0,6096106	.	.
Location	1	1	0,8686989	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	6,9541545	.	6,95415
small	5,9369326	.	5,93693

Buttons

Least Squares Means Table

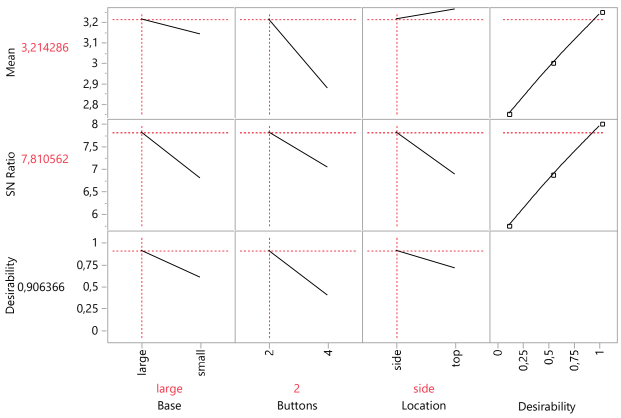
Level	Least Sq Mean	Std Error	Mean
2	6,8359313	.	6,83593
4	6,0551557	.	6,05516

Location

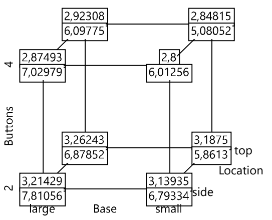
Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	6,9115636	.	6,91156
top	5,9795234	.	5,97952

Prediction Profiler



Cube Plot



Least Squares Fit

Effect Summary

Source	LogWorth	PValue
Base	0,000	1,00000
Buttons	0,000	1,00000
Location	0,000	1,00000

Response Mean

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3,3585165	.	.	.
Base[large]	-0,179945	.	.	.
Buttons[2]	0,0233516	.	.	.
Location[side]	-0,130495	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,12952089	.	.
Buttons	1	1	0,00218120	.	.
Location	1	1	0,06811526	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	3,1785714	.	3,17857
small	3,5384615	.	3,53846

Buttons

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
2	3,3818681	.	3,38187
4	3,3351648	.	3,33516

Location

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	3,2280220	.	3,22802
top	3,4890110	.	3,48901

Response SN Ratio

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	8,8336194	.	.	.
Base[large]	-0,102041	.	.	.
Buttons[2]	0,393938	.	.	.
Location[side]	-0,697397	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,0416491	.	.
Buttons	1	1	0,6207486	.	.
Location	1	1	1,9454514	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	8,7315788	.	8,73158
small	8,9356600	.	8,93566

Buttons

Least Squares Means Table

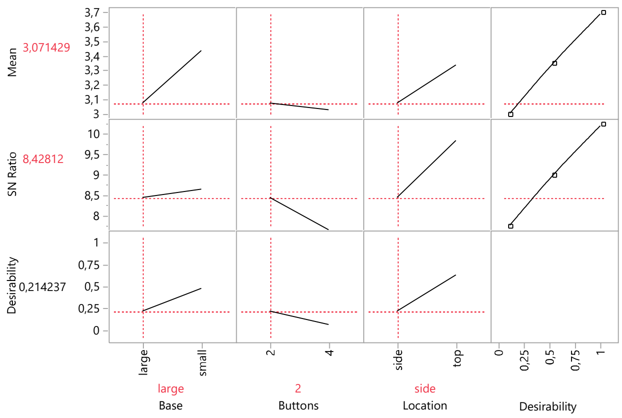
Level	Least Sq Mean	Std Error	Mean
2	9,2275574	.	9,22756
4	8,4396814	.	8,43968

Location

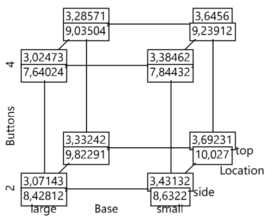
Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	8,1362222	.	8,13622
top	9,5310166	.	9,53102

Prediction Profiler



Cube Plot



Least Squares Fit

LoFi_Ease of use

Effect Summary

Source	LogWorth	PValue
Base	0,000	1,00000
Buttons	0,000	1,00000
Location	0,000	1,00000

Response Mean

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3,2898352	.	.	.
Base[large]	0,0398352	.	.	.
Buttons[2]	0,1744505	.	.	.
Location[side]	-0,075549	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,00634736	.	.
Buttons	1	1	0,12173198	.	.
Location	1	1	0,02283088	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	3,3296703	.	3,32967
small	3,2500000	.	3,25000

Buttons

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
2	3,4642857	.	3,46429
4	3,1153846	.	3,11538

Location

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	3,2142857	.	3,21429
top	3,3653846	.	3,36538

Response SN Ratio

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	6,9883307	.	.	.
Base[large]	0,3097692	.	.	.
Buttons[2]	0,7132594	.	.	.
Location[side]	0,0814339	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,3838277	.	.
Buttons	1	1	2,0349560	.	.
Location	1	1	0,0265259	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	7,2980999	.	7,29810
small	6,6785616	.	6,67856

Buttons

Least Squares Means Table

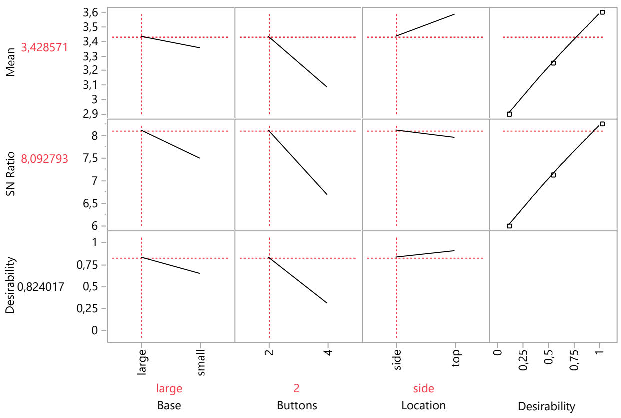
Level	Least Sq Mean	Std Error	Mean
2	7,7015901	.	7,70159
4	6,2750713	.	6,27507

Location

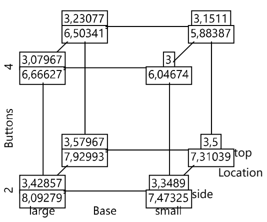
Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	7,0697647	.	7,06976
top	6,9068968	.	6,90690

Prediction Profiler



Cube Plot



HiFi_Ease of use

Least Squares Fit

Effect Summary

Source	LogWorth	PValue
Base	0,000	1,00000
Buttons	0,000	1,00000
Location	0,000	1,00000

Response Mean

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3,7362637	.	.	.
Base[large]	-0,271978	.	.	.
Buttons[2]	0,1291209	.	.	.
Location[side]	-0,093407	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,29588818	.	.
Buttons	1	1	0,06668881	.	.
Location	1	1	0,03489917	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	3,4642857	.	3,46429
small	4,0082418	.	4,00824

Buttons

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
2	3,8653846	.	3,86538
4	3,6071429	.	3,60714

Location

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	3,6428571	.	3,64286
top	3,8296703	.	3,82967

Response SN Ratio

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	10,588056	.	.	.
Base[large]	-0,757702	.	.	.
Buttons[2]	0,470279	.	.	.
Location[side]	-0,16764	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	2,2964475	.	.
Buttons	1	1	0,8846495	.	.
Location	1	1	0,1124125	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	9,830354	.	9,8304
small	11,345758	.	11,3458

Buttons

Least Squares Means Table

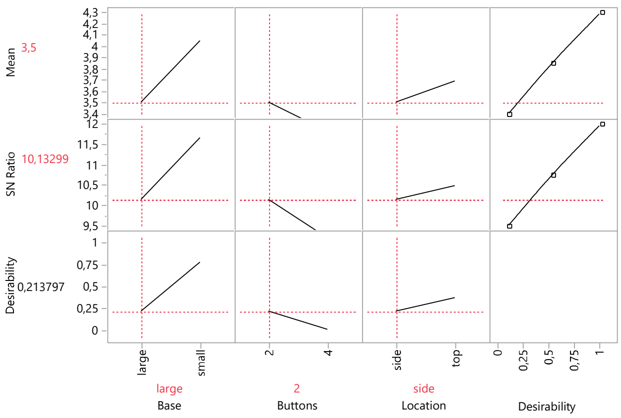
Level	Least Sq Mean	Std Error	Mean
2	11,058335	.	11,0583
4	10,117777	.	10,1178

Location

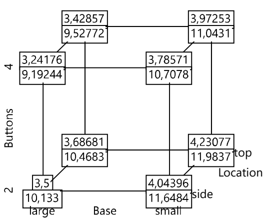
Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	10,420416	.	10,4204
top	10,755696	.	10,7557

Prediction Profiler



Cube Plot



Least Squares Fit

Effect Summary

Source	LogWorth	PValue
Base	0,000	1,00000
Buttons	0,000	1,00000
Location	0,000	1,00000

Response Mean

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	2,7391484	.	.	.
Base[large]	-0,035852	.	.	.
Buttons[2]	-0,007005	.	.	.
Location[side]	0,0179945	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,00514136	.	.
Buttons	1	1	0,00019631	.	.
Location	1	1	0,00129521	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	2,7032967	.	2,70330
small	2,7750000	.	2,77500

Buttons

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
2	2,7321429	.	2,73214
4	2,7461538	.	2,74615

Location

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	2,7571429	.	2,75714
top	2,7211538	.	2,72115

Response SN Ratio

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	4,7637358	.	.	.
Base[large]	0,1721477	.	.	.
Buttons[2]	0,6937263	.	.	.
Location[side]	0,1255926	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,1185394	.	.
Buttons	1	1	1,9250248	.	.
Location	1	1	0,0630940	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	4,9358835	.	4,93588
small	4,5915880	.	4,59159

Buttons

Least Squares Means Table

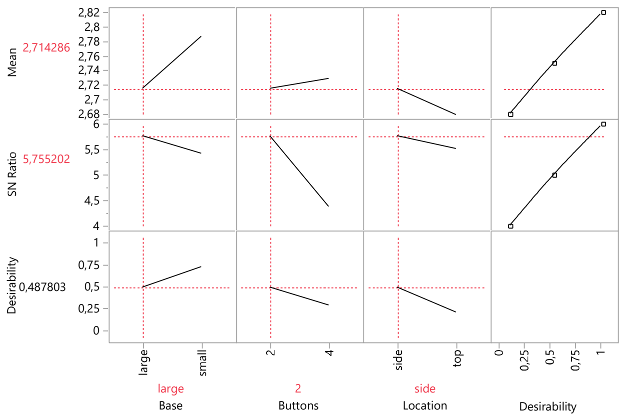
Level	Least Sq Mean	Std Error	Mean
2	5,4574621	.	5,45746
4	4,0700095	.	4,07001

Location

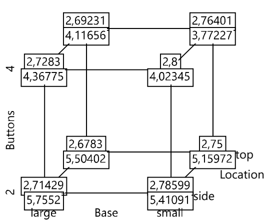
Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	4,8893284	.	4,88933
top	4,6381431	.	4,63814

Prediction Profiler



Cube Plot



Least Squares Fit

Effect Summary

Source	LogWorth	PValue
Base	0,000	1,00000
Buttons	0,000	1,00000
Location	0,000	1,00000

Response Mean

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3,6524725	.	.	.
Base[large]	0,0260989	.	.	.
Buttons[2]	0,0453297	.	.	.
Location[side]	0,1332418	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,00272461	.	.
Buttons	1	1	0,00821912	.	.
Location	1	1	0,07101346	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	3,6785714	.	3,67857
small	3,6263736	.	3,62637

Buttons

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
2	3,6978022	.	3,69780
4	3,6071429	.	3,60714

Location

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	3,7857143	.	3,78571
top	3,5192308	.	3,51923

Response SN Ratio

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	7,7204865	.	.	.
Base[large]	0,5080783	.	.	.
Buttons[2]	0,487124	.	.	.
Location[side]	1,3669536	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	1,0325742	.	.
Buttons	1	1	0,9491591	.	.
Location	1	1	7,4742490	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	8,2285648	.	8,22856
small	7,2124082	.	7,21241

Buttons

Least Squares Means Table

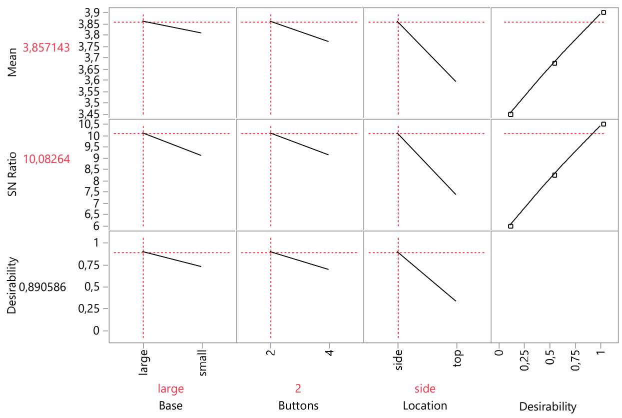
Level	Least Sq Mean	Std Error	Mean
2	8,2076105	.	8,20761
4	7,2333625	.	7,23336

Location

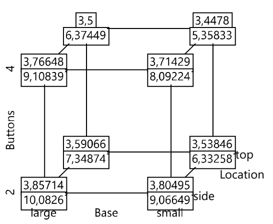
Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	9,0874401	.	9,08744
top	6,3535329	.	6,35353

Prediction Profiler



Cube Plot



LoFi_I would choose this

Least Squares Fit

Effect Summary

Source	LogWorth	PValue
Base	0,000	1,00000
Buttons	0,000	1,00000
Location	0,000	1,00000

Response Mean

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	2,3283425	.	.	.
Base[large]	-0,179991	.	.	.
Buttons[2]	0,1180861	.	.	.
Location[side]	-0,123581	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,12958681	.	.
Buttons	1	1	0,05577729	.	.
Location	1	1	0,06108865	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	2,1483516	.	2,14835
small	2,5083333	.	2,50833

Buttons

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
2	2,4464286	.	2,44643
4	2,2102564	.	2,21026

Location

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	2,2047619	.	2,20476
top	2,4519231	.	2,45192

Response SN Ratio

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	4,2577041	.	.	.
Base[large]	-0,496649	.	.	.
Buttons[2]	0,3364922	.	.	.
Location[side]	-0,305763	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,98663961	.	.
Buttons	1	1	0,45290798	.	.
Location	1	1	0,37396477	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	3,7610555	.	3,76106
small	4,7543528	.	4,75435

Buttons

Least Squares Means Table

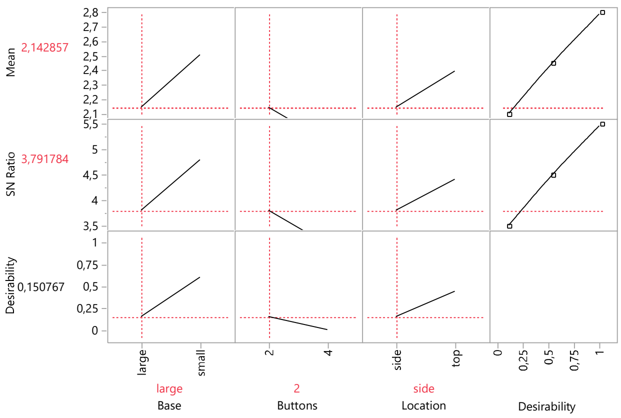
Level	Least Sq Mean	Std Error	Mean
2	4,5941963	.	4,59420
4	3,9212119	.	3,92121

Location

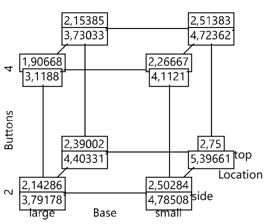
Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	3,9519408	.	3,95194
top	4,5634674	.	4,56347

Prediction Profiler



Cube Plot



HiFi_Ottaisin tämän – Fit Least Squares

HiFi_I would choose this

Least Squares Fit

Effect Summary

Source	LogWorth	PValue
Base	0,000	1,00000
Buttons	0,000	1,00000
Location	0,000	1,00000

Response Mean

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	2,9313187	.	.	.
Base[large]	-0,145604	.	.	.
Buttons[2]	0,0384615	.	.	.
Location[side]	-0,038462	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,08480256	.	.
Buttons	1	1	0,00591716	.	.
Location	1	1	0,00591716	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	2,7857143	.	2,78571
small	3,0769231	.	3,07692

Buttons

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
2	2,9697802	.	2,96978
4	2,8928571	.	2,89286

Location

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	2,8928571	.	2,89286
top	2,9697802	.	2,96978

Response SN Ratio

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	5,3711177	.	.	.
Base[large]	-0,61491	.	.	.
Buttons[2]	0,1504218	.	.	.
Location[side]	0,1206728	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	1,5124590	.	.
Buttons	1	1	0,0905069	.	.
Location	1	1	0,0582477	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	4,7562074	.	4,75621
small	5,9860281	.	5,98603

Buttons

Least Squares Means Table

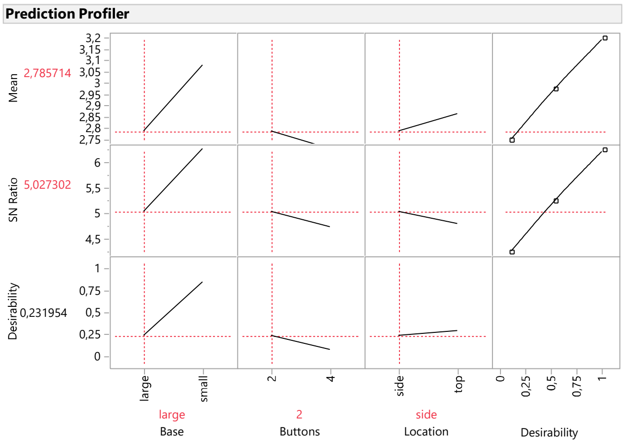
Level	Least Sq Mean	Std Error	Mean
2	5,5215395	.	5,52154
4	5,2206959	.	5,22070

Location

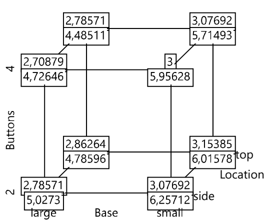
Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	5,4917905	.	5,49179
top	5,2504449	.	5,25044

Prediction Profiler



Cube Plot



Least Squares Fit

Effect Summary

Source	LogWorth	PValue
Base	0,000	1,00000
Buttons	0,000	1,00000
Location	0,000	1,00000

Response Mean

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	4,1830929	.	.	.
Base[large]	0,0476763	.	.	.
Buttons[2]	-0,022035	.	.	.
Location[side]	0,1758814	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,00909211	.	.
Buttons	1	1	0,00194221	.	.
Location	1	1	0,12373708	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	4,2307692	.	4,23077
small	4,1354167	.	4,13542

Buttons

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
2	4,1610577	.	4,16106
4	4,2051282	.	4,20513

Location

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	4,3589744	.	4,35897
top	4,0072115	.	4,00721

Response SN Ratio

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	11,034494	.	.	.
Base[large]	0,5105214	.	.	.
Buttons[2]	-0,66987	.	.	.
Location[side]	1,0085894	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	1,0425282	.	.
Buttons	1	1	1,7949046	.	.
Location	1	1	4,0690103	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	11,545015	.	11,5450
small	10,523973	.	10,5240

Buttons

Least Squares Means Table

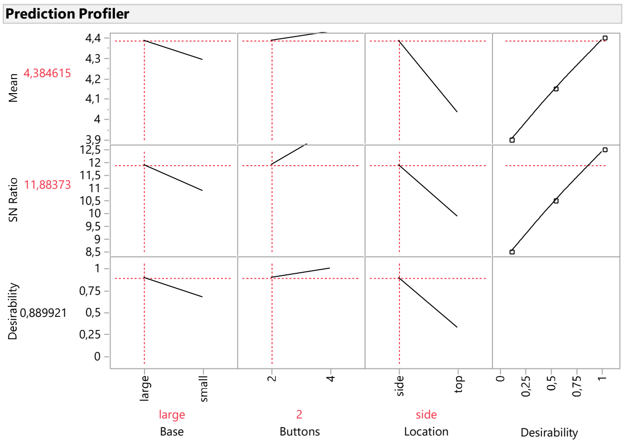
Level	Least Sq Mean	Std Error	Mean
2	10,364624	.	10,3646
4	11,704364	.	11,7044

Location

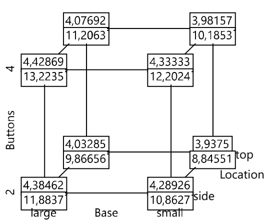
Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	12,043083	.	12,0431
top	10,025905	.	10,0259

Prediction Profiler



Cube Plot



Least Squares Fit

Effect Summary

Source	LogWorth	PValue
Base	0,000	1,00000
Buttons	0,000	1,00000
Location	0,000	1,00000

Response Mean

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	4,1497253	.	.	.
Base[large]	-0,006868	.	.	.
Buttons[2]	0,2568681	.	.	.
Location[side]	0,0288462	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,00018868	.	.
Buttons	1	1	0,26392495	.	.
Location	1	1	0,00332840	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	4,1428571	.	4,14286
small	4,1565934	.	4,15659

Buttons

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
2	4,4065934	.	4,40659
4	3,8928571	.	3,89286

Location

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	4,1785714	.	4,17857
top	4,1208791	.	4,12088

Response SN Ratio

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	11,754179	.	.	.
Base[large]	-0,049608	.	.	.
Buttons[2]	0,8197042	.	.	.
Location[side]	0,0940879	.	.	.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Base	1	1	0,0098438	.	.
Buttons	1	1	2,6876596	.	.
Location	1	1	0,0354102	.	.

Effect Details

Base

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
large	11,704571	.	11,7046
small	11,803786	.	11,8038

Buttons

Least Squares Means Table

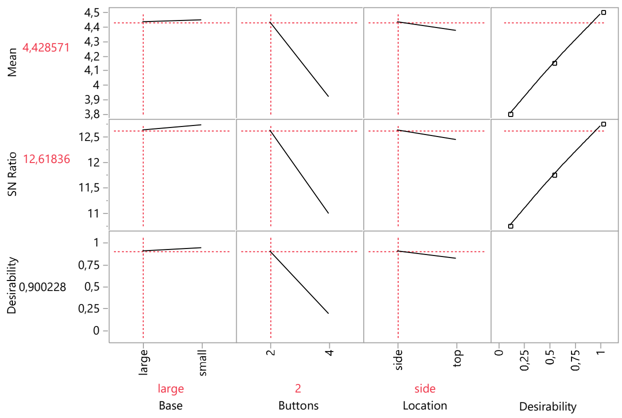
Level	Least Sq Mean	Std Error	Mean
2	12,573883	.	12,5739
4	10,934474	.	10,9345

Location

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
side	11,848267	.	11,8483
top	11,660091	.	11,6601

Prediction Profiler



Cube Plot